NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

> ## A COMPARISON OF THE FORCE DEPLOYMENT ESTIMATOR (FDE) AND NAVAL POSTGRADUATE SCHOOL / RAND MOBILITY OPTIMIZER (NRMO) AS TOOLS FOR MOBILITY ANALYSIS
>
> by
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Over the past decade, changes in the global power structure have driven the United States into a major reassessment of its force structure and global force projection requirements. There is a resulting need for force deployment models that offer quick, accurate analysis of force projection and force structure options. One model, the Force Deployment Estimator (FDE), a combination discrete event simulation and goal program, is currently used by the J8/WAD. A second model with similar capabilities, the Naval Postgraduate School / RAND Mobility Optimizer (NRMO), is a linear program that was written for the Air Force. In order to compare the two models and give J8/WAD the option of a second model for use in analysis, NRMOAS (NRMO Air/Sea) was created by adding a sealift component to NRMO. NRMOAS creates both an air and sea network. and can be run with the user designating the unit's mode of travel (similar to FDE), the model determining the same or a combination of both. This thesis compares the results of scenarios run through FDE and NRMOAS and recommends to J8/WAD which model better suits their needs. In all cases, NRMOAS outperformed FDE. NRMOAS also offers a superior level of resolution for networks. Recommend that J8/WAD use NRMOAS for detailed mobility analysis.

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A COMPARISON OF THE FORCE DEPLOYMENT ESTIMATOR (FDE) AND NAVAL POSTGRADUATE SCHOOL / RAND MOBILITY OPTIMIZER (NRMO) AS TOOLS FOR MOBILITY ANALYSIS

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ABSTRACT

Over the past decade, changes in the global power structure have driven the United States into a major reassessment of its force structure and global force projection requirements. There is a resulting need for force deployment models that offer quick, accurate analysis of force projection options and proposed force structure changes. One model, the Force Deployment Estimator (FDE), a combination discrete event simulation and goal program, is currently used by the J8, Warfighting Analysis Division (J8/WAD). A second model with similar capabilities, the Naval Postgraduate School / RAND Mobility Optimizer (NRMO), is a linear program that was written for the Air Force Studies and Analysis Agency. In order to compare the two models and give J8/WAD the option of a second model for use in analysis, NRMOAS (NRMO Air/Sea) was created by adding a sealift component to NRMO. NRMOAS creates both an air and sea network and can be run with the user designating the unit's mode of travel, the model determining the same or a combination of both. This thesis compares the results of several different scenarios run through FDE and NRMOAS. In all cases tested, NRMOAS out-performed FDE in terms of timely delivery of personnel and cargo. Additionally, NRMOAS allows a far higher level of resolution in network structure. Recommendation to J8/WAD is that NRMOAS be used for detailed mobility analysis. Also recommend are changes to FDE to improve its usefulness.

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EXECUTIVE SUMMARY

Over the past decade, changes in the global power structure have driven the United States into a major reassessment of its force structure and global force projection requirements. Numerous studies have established a need for models that are flexible, and can offer quick, accurate analysis of force projection options and proposed force structure changes. The J-8, Warfighting Analysis Division (J-8/WAD)'s current tool for analyses of this nature is the Force Deployment Estimator (FDE), a combination discrete event simulation and goal programming model provided by SETA Corporation. Because FDE does not achieve optimal solutions and it sometimes does not complete execution, it is desirable for J-8/WAD to have a second model to compare against FDE.

The Naval Postgraduate School / RAND Mobility Optimization model (NRMO), a linear optimization model that considers airlift only, has many similar capabilities to FDE. The purpose of this thesis is to make a comparison of the two and recommend to J8/WAD which one better suits their needs. In order for NRMO to be useful to J-8/WAD and comparable to FDE, it must also handle sealift. This additional capability required several augmentations to the existing NRMO model, which are developed in this thesis. The result is the Naval Postgraduate School / RAND Mobility Optimizer, Air / Sea (NRMOAS), a version of NRMO that allows the model to conduct both airlift and sealift operations. In order for NRMOAS to set up both an air and sea network, it was necessary to add sets to distinguish airfields from ports, aircraft from ships (referred to jointly as "vehicles"), and air ports of embarkation (APOEs) from seaports of embarkation (POEs). These additions also required the separation of the variables used to make initial allocation of vehicles. Once initially allocated, ships travel only on sea routes and aircraft only on air routes, so all other constraints can be used by both aircraft

and ships without fear of redundant or conflicting use of assets. Other changes that were required dealt with port capacity and fuel consumption constraints. In addition, J-8/WAD required that the model allow the user to track the by-day delivery of every unit's cargo and personnel. This calculation was added to NRMO. Values for ship speed, capacity, load and unload times and fuel consumption were taken directly from FDE. Where information was unavailable, it was developed from military manuals, phone calls and existing data sets. NRMOAS operates with two types of travel mode selection: user designated and model designated. This required the compilation of aircraft / ship load tables that were a composite of those found both in NRMO (units by air only) and FDE (units by air or ship, but not both).

Once developed, three scenarios were run through NRMOAS and FDE. FDE was extremely challenging to work with and demonstrated several major restrictions in its ability to represent an actual network. Paths with more than four links are not tolerated by the model, making accurate depiction of deployment networks virtually impossible. Similarly, scenarios with a large number of source nodes aand a small amount of cargo caused FDE to crash. Difficulties were also encountered building the FDE data sets. In most caes, FDE files are built using a legacy file which contains extensive unit and carrier information. This file serves as a shell from which desired scenarios are built. Building files from scratch is extremely challenging and is, in fact, highly discouraged by experienced FDE users. Specific problems include: FDE's inability to utilize a path that has any more than four links, and FDE's inability to handle a network designed with multiple source nodes and small amounts of cargo. Eventually, data was sent to a SETA analyst who built the closest representation of the desired deployment network that could be designed. Once FDE was running, no more than 26 trial

solutions could be requested for any problem. Any number higher than that again caused the model to crash.

Once results were obtained from FDE, comparison were made between the two models. NRMOAS out-performed FDE in terms of timely delivery of cargo and personnel in all runs. Totaling the units from all three scenarios, NRMOAS delivered 67.7% of unit cargo and 65.1% of unit personnel on-time compared to FDE's 44.00% for unit cargo and 41.3% for unit personnel. NRMOAS also achieved a high on-time delivery rate of 95.8% for unit cargo and 100.0% for unit personnel compared to FDE's highs of 70.8% and 80.3%, respectively. NRMOA's superior performance was attributed to better utilization of assets available.

There are two final conclusions. First, if FDE is to be retained as a tool for analysis in J8/WAD, it requires major improvements in its ability to accurately represent deployment networks. The initial allocation algorithm, the graphical user interface and the extreme difficulty in building files from scratch must also be addressed. The second conclusion is that NRMOAS's superior performance and higher level of resolution for networks and infrastructure make it a better tool for analysis than FDE. Recommendation to J8/WAD is that NRMO be adopted as their main tool for detailed analysis, while FDE can be used for broad brush mobility questions that don't require a high degree of network resolution.

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I. INTRODUCTION

A. BACKGROUND

Over the past decade, changes in the global power structure have driven the United States into a major reassessment of its force structure and global force projection requirements. The Mobility Requirements Study (MRS) of 1990, the MRS Bottom Up Review Update (MRS BURU) of 1992, the Quadrennial Defense Review of 1996, and numerous other smaller, more limited studies, have established a need for models that can offer quick, accurate analysis of force projection requirements and proposed force structure changes. Because these taskings can run the gamut from major force deployment studies of the magnitude of DESERT SHIELD / DESERT STORM to the effects of adding to or deleting strategic lift capabilities, the required models should be flexible.

B. PROBLEM STATEMENT

The J-8 (Force Structure, Resources and Assessment) section of the Joint Chiefs of Staff is often tasked with conducting these types of studies. Within the J-8, these taskings normally fall to the Warfighting Analysis Division (J-8/WAD). In most cases, J-8/WAD is concerned with the following general types of questions:

1. How long will it take to get units and cargo to the Area of Operations?

2. What is the most efficient use of the assets available?

3. What is the affect of changes in specific assets?

4. What is the affect of changes in infrastructure?

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J-8/WAD's current tool for analyses of this nature is the Force Deployment Estimator (FDE) (FDE URM, 1996), provided by SETA Corporation. FDE combines a discrete event simulation and goal programming model. It is used both to generate force arrival profiles and to conduct sensitivity analysis on the results. Because FDE does not achieve optimal solutions and it sometimes does not complete execution, it is desirable for J-8/WAD to have a second model to compare against FDE. The Naval Postgraduate School / RAND Mobility Optimization model (NRMO) (Melody, et al, 1997) is a linear optimization model that considers airlift only. With the addition of a sealift component, NRMO could offer J-8/WAD a viable alternative to FDE. The purpose of this thesis is to add a sealift component to NRMO, compare that model with FDE and make a recommendation to J-8/WAD as to which model better suits their needs.

II. MODEL REVIEW

A. FORCE DEPLOYMENT ESTIMATOR

1. Overview

The Force Deployment Estimator (FDE) is designed to provide quick analysis of deployment and sustainment issues as they relate to contingency plans (FDE URM, 1998, p. 1-1). Specifically, it is designed to answer the following questions:

   a. Can the forces be deployed to the theater on time (as defined by the required delivery date)? If not, how close can they get?

   b. What are the most likely arrival times for forces?

   c. What are the most important factors contributing to the arrival times for the forces?

   d. How will the answers to the above questions change if the theater deployment is delayed by late availability of units or lift assets; by enemy attacks on ports or airfields; or by closure of vital choke points such as straits, canals, or shipping lanes caused by enemy minefields? (FDE URM, 1998, p. 3-1)

FDE allows sensitivity analysis over a variety of issues. By varying input, users can parametrically assess a war plan with respect to variations in force structure, lift capabilities, phasing of units and any number of questions that arise during force structure analysis.

2. History

FDE 1.0 was developed by Los Alamos National Laboratory and released in April of 1992. Originally written in FORTRAN, it underwent its first major overhaul by Potomac Systems Engineering and was released as FDE 2.0 in September of 1994. FDE 2.0 added stochastic loading time variables in an effort to make a more realistic appraisal of deployment requirement times. The next upgrade, FDE 3.0, was released by SETA Corporation in October

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of 1996. FDE 3.0 is a major revision, including conversion to C++ and the addition of a graphical user interface. SETA also advertised that FDE 3.1 would contain a simulated annealing capability. This capability was supposed to yield a 5 to 20 times increase in run time and to provide globally optimal solutions (FDE URM, 1998, p. 3-9). FDE 3.1 was released in April of 1998, but did not contain the simulated annealing capability and in fact showed no significant difference from version 3.0. It does not provide global optima. FDE 3.1 is the version that will be used for comparison with NRMO.

3.   Features

FDE's primary function is the efficient assignment of lift platforms for deployment and sustainment of units, in support of war plans. Assignment of cargo to carriers and carriers to routes is made within the constraints set by the user. The model "solves" the problem based on four specific goals:

1. Minimize closure time deviations for units. (Closure time deviation is defined as the number of days after the required delivery date (rdd) that a unit arrives in theater.)

2. Minimize the dispersion of delivery times for each unit. (Dispersion is defined as the time between consecutive deliveries of a unit's cargo and personnel.)

3. Minimize the cost of the deployment. (An actual dollar value for operation of each type of lift asset can be added to the problem.)

4. Minimize the number of carrier reallocations. (Lift assets are initially allocated at random or are assigned to specific bases by the user. They are "re-allocated" if they must be moved empty from one embarkation base to another during the execution of the simulation.)

These goals may be used singly or in any combination, as specified by the user. If no goal is specified, FDE takes the first goal as the default. (FDE URM, 1998, p. 3-4)

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FDE's methodology can be described as a combination of discrete event simulation, goal programming and Monte Carlo search techniques (FDE URM, 1998, p. 3-1). The discrete event simulator is the portion of code that "executes" the deployment. The goal program is not an actual goal program, as defined in the linear programming literature [Dantzig and Thapa, 1997], but simply a method to check the solution to see if it meets the goals, as selected by the user. The simulation runs as many times as the user specifies, saves all the solutions and then picks the "best" one, in terms of meeting the user defined goals. The URM states that the solution will be a local, but not necessarily global optimum (FDE URM, 1998, p.3-6). There is no substantiation to this claim.

4. Organization

FDE is organized into three main components: a data management facility, a modeling kernel and a graphical user interface (FDE URM, 1998, p. 2-3).

The data management facility is composed of a large internal data file and numerous output files. To operate, FDE requires input from formatted data files. These can be generated from the internal data file or input via the graphical user interface. The internal data file contains legacy files called "fort.1" files. These files have been developed over time and contain large amounts of data related to unit loading requirements and cargo carrier capacity. The "fort.1" files can be used as a starting point from which to build current data sets, with additional required elements input via the GUI. The ten output files are written in two formats: reports and graphs. Specific output file information is shown in Appendix A. (FDE URM, 1998, p. 2-2)

The modeling kernel contains the actual mathematical algorithms used to solve the problem. It has three main components; the discrete event simulator, the so called goal programming model and a Monte Carlo simulation.

The discrete event simulation is the core of FDE and actually "executes" the deployment simulation. The simulation itself contains four major algorithms. The first algorithm makes the initial assignments of carriers to units. This is done in direct proportion to the tonnage requirements of the unit and in inverse proportion to the square of the product of the unit priority and required arrival date, while also considering what types of cargo the carrier can move. The user may over-ride this algorithm by pre-assigning carriers to specific start points or units. The second algorithm contains the logic which re-assigns carriers once they have completed their current delivery. It is similar in process to the initial assignment algorithm, so the carrier will be re-assigned to the node that needs it the most. (FDE URM, 1998, p. 3-16)

The third algorithm is the aircraft loading algorithm. This algorithm considers five separate loading cases, based on allowable load combinations and aircraft capacity. The amount of personnel or cargo an aircraft can carry is determined from load factors designed by the US Air Force Studies and Analyses Agency for the MIDAS model (FDE URM, 1998, p. 3-16). The algorithm also accounts for the amount of cargo and personnel moved throughout the simulation. Algorithm specifics are shown in Appendix A.

The final algorithm is the ship and rail loading algorithm. The actual logic used in this algorithm comes from the Carrier Payload tables in the FDE database. Once the algorithm determines whether the carrier in question is a ship or train, it checks to see if the cargo that is available to be loaded is greater than or equal to the carrier's capacity, as measured in tons of cargo per unit type. If so, the carrier is loaded until full and it departs for its destination. If not, the carrier loads all available cargo and the model looks for any other cargo enroute to the same destination. If such cargo exists, the carrier waits until this cargo is delivered and loaded. If not, the carrier departs. (FDE URM, 1998, p. E-1)

The modeling kernel also contains the goal programming algorithm. What FDE calls a goal programming algorithm is not an actual goal program as defined in linear programming literature. (FDE URM, 1998, p. 3-6) In actuality, it simply takes the current solution and compares it against the "best" solution found to that point, in terms of meeting the user defined goals. If the new solution comes closer to meeting these goals, it becomes the new "best" solution. The URM is not specific about how this comparison takes place. Following the comparison, the program checks to see if the simulation should be run again, based on a user defined number of iterations. This continues until the required number of simulations has been completed. A better name for the FDE goal programming module would be a "goal evaluator".

The final part of the modeling kernel is the Monte Carlo simulation, which randomly allocates carriers to specific nodes and paths throughout the network. This is repeated at the start of every run of the simulation. The number of desired simulation runs is set by the user. SETA advertises that if the number of runs is sufficiently large (i.e. 25 to 75), the results will be very close to a global optimal. (FDE URM, 1998, p. 3-9) No substantiation to this statement is offered. This would be a unique result in the operations research literature if it were proven.

The graphical user interface ties the data and related file utilities to the modeling kernel (FDE URM, 1998, p. 2-3). It is a standard Windows-based product, with five types of windows. The main window appears when the program is started and is the window through which all other windows are started and accessed. Dialog windows provide secondary interface with FDE and appear over the main window. File selection windows allow the user to select specific files from various directories and sub-directories. Selection windows are contained within other windows and allow the user to make selections from lists of choices contained in the window. Finally, message windows are used to send messages to the reader. They include

information dialog, question dialog, working dialog and warning dialog. (FDE URM, 1998, p. 4-4)

5.   Hardware

FDE was designed and tested to run on a SUN SPARC system. Currently, J-8/WAD runs FDE on SUN/UNIX work stations, but it can also run on stand-alone units. It requires 1.3 gigabytes of hard disk. In addition, 300 megabytes of swap-space is recommended to allow FDE to build temporary matrices when solving problems, for a total requirement of 1.6 gigabytes. FDE requires no additional software. (FDE URM, 1998, p. 2-3)

6.   Assumptions and Restrictions

FDE's documentation includes fourteen stated assumptions. The most critical assumption is that FDE is designed as an operational planning tool and not as a logistics planner. The logistics planning factors are sufficient to answer force deployment questions, but not detailed logistical questions. In particular, a high level of aggregation of unit cargo and base infrastructure would make FDE ineffective as a logistical planning tool. Moreover, FDE is designed to analyze initial deployments, defined as activity prior to the establishment of a logistics pipeline. During the initial phase, deploying units and sustainment requirements compete for assets equally. FDE assumes that once a logistics pipeline is established, sustainment will no longer be required to compete for assets, but will have specific assets dedicated to its movement (FDE URM, 1998, p. 3-2). Additional assumptions deal with modeling issues and are listed in Appendix A.

J-8 imposed three restrictions on the designers of FDE. First, given a scenario and the input, FDE must run in under 30 minutes. (This restriction was non-specific as to the platform used or the number of simulation runs required.) Second, all events that take place during the simulation must be physically realistic. For example, a shipping route cannot cross a land mass,

but must navigate around it. Finally, the model must be "user-friendly". (FDE URM, 1998, p. 3-2)

7. Input

FDE categorizes scenario information into five parts, which are defined below:

a. Lift Assets (Carriers). These are defined as those items that can transport personnel and/or cargo from port to port. FDE lift assets include aircraft, shipping, trucks and trains. Lift asset information includes average speed and capacity, broken down by cargo types.

b. Deployment Requirements. These include the actual units, their equipment, destination, point of origin, date available to move, required delivery date and unit priority.

c. Network. This is the node-arc network of routes available for the deployment. Nodes are defined by longitude and latitude, carrier types that can use them and carrier capacity. Arcs are defined by the nodes they connect and the carriers that can travel on them.

d. Goals. These are defined by the user and were listed earlier. Any combination, including all four, can be selected.

e. Constraints. These are derived from the scenario. They include items such as availability of assets or restrictions on certain carrier/cargo combinations, barriers to carrier/path combinations or degradation of certain nodes or arcs due to enemy activity. Route or node degradation is provided as user inputs.

(FDE URM, 1998, p. 3-3)

Start

Monte Carlo Initial Path Allocation → Discrete Event Simulator → Goal Evaluation Save Best Soln → More

Yes

No

Improve

No

Yes

Exit Best Solution

Simulated Annealing*
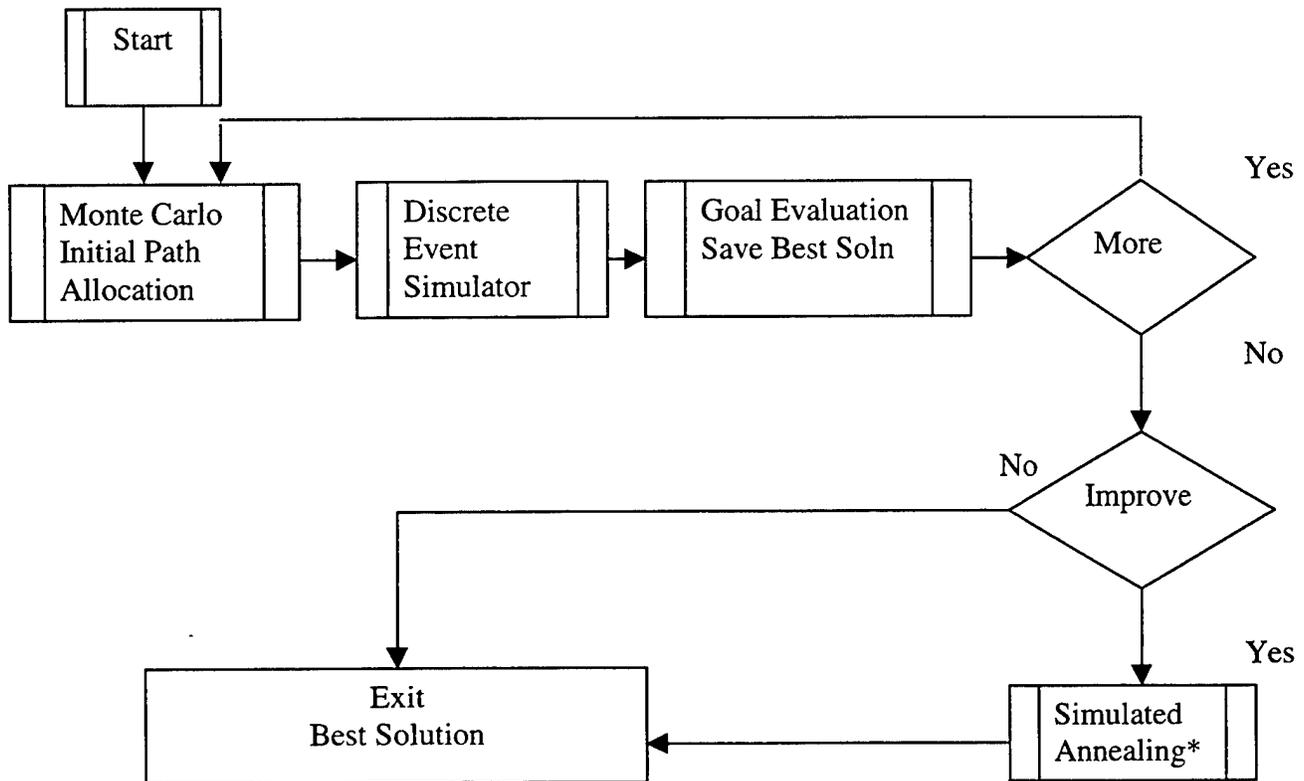
* Not Implemented

Figure 1. This flow diagram depicts the primary modules of the solution algorithm. This methodology is not a single program, but rather a series of three techniques that work together until one of three things happens: a feasible solution is achieved, the model "cut-off" criterion is reached, or a specific number of solutions are generated (FDE URM, 1998, p. 3-5).

8.   Solution Method

The solution method uses three separate mathematical techniques that interact iteratively (FDE URM, 1998, p.3-5). This method is pictured in Figure 1. When solving the problem, FDE first determines if there is a feasible solution to the allocation of lift to satisfy all the goals. If not, FDE will allocate assets to achieve a solution that is as close to feasible as possible, i.e. the "best" possible solution (FDE URM, 1998, p. 3-1). FDE can be used in either a simple or a variable mode.

The simple mode is the most commonly used. Input values such as speed, carrier capacity, etc. are fixed at their expected value. The program runs a user defined number of trials and the solution which comes closest to meeting the user defined goals is given. Simple mode is normally used when trying to answer the question, "Can forces be deployed to the theater on time?" or "What is the most likely theater deployment time?" (FDE URM, 1998, p. 3-10)

In the variable mode, the user chooses both the number of simulation runs and the number of trials within each run. First, the model finds a run's "best" solution. Then it conducts sensitivity analysis on this solution by drawing a value for each variable from a given probability distribution and running the solution with that data. This "draw and solve" cycle is repeated for whatever number of trials the user chooses. The model then performs an Analysis of Variance (ANOVA) on these results and gives each solution's mean, variance and most likely result. FDE URM, 1998, p. 3-11)

9.   Results

Results from FDE can be used either in a report or graphical format. FDE's results are most commonly used to answer the four questions that were stated at the beginning of the section on FDE. In addition, sensitivity analysis can easily be carried out by varying input parameters and observing how that changes results. Analysis of this type can then be used to gain insight into force structure questions from a force deployment standpoint. For example, questions such as increasing or decreasing the number of a certain type of carrier or heavy versus light divisions can be considered with an eye towards their effect on the United States' ability to deploy its forces abroad with a given fleet of lift assets. FDE can also be used to "wargame" deployment plans and determine how the loss or addition of assets will affect these plans.

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B. NAVAL POSTGRADUATE SCHOOL / RAND MOBILITY OPTIMIZER (NRMO)

1. Overview

NRMO was designed to help planners and analysts answer the airlift force structure and infrastructure questions that are associated with force deployment issues. Typical of these types of questions are:

a. Are the given fleet and infrastructure assets adequate for deployment?

b. Where are the system bottlenecks? When do they matter? How much do they limit airlift capacity?

c. What changes in mobility concepts of operation would improve performance? What about the affects of reduced closure time (defined as the arrival of a unit's personnel and cargo) or reduced resource expenditures?

d. How do the results differ across scenarios?

(Melody, et al., 1997, p. v)

NRMO has been used to conduct airlift force structure analysis, infrastructure analysis and concept of operations analysis using a single model.

2. History and Genealogy

Development of NRMO began in May of 1996 as a cooperation between the Naval Postgraduate School (NPS) and RAND. At that time, NPS was under contract to the Air Force Studies and Analysis Agency (AFSAA) for work in the area of air mobility. RAND, who had previously done a significant amount of research in this field, began their portion of the work in response to a direct-assistance request from Headquarters, United States Air Force. AFSAA desired that NPS and RAND work together in an attempt to create a single optimization model that incorporated all the best features of past models. NRMO was the result. The current model is under the cognizance of the Air Force Studies and Analysis Agency (AFSAA). In addition to continuing research being done by NPS and RAND, other users include Air Mobility

Command; Air Force Institute of Technology; J-8/Warfighting Analysis Division, JCS; U.S. Air Force Academy; University of Texas at Austin; and Washington University, St. Louis.

NRMO can trace its lineage to four main models; Mobility Optimization Model (MOM) (Wing, et al, 1991), THRUPUT1 (Yost, 1994), CONOP (Killingsworth and Melody, 1997), and THRUPUT2 (Morton, et al, 1996). MOM, developed by J-8 and NPS, incorporated both sealift and airlift in a time-dynamic model with a simple geographical network representation. THRUPUT1, developed in 1991 by AFSAA had an extensive geographical network, but was a steady state model. THRUPUT2, developed by NPS for AFSAA in 1994-5, combined the dynamics of MOM and the extensive geographic representation of THRUPUT1 into a single model. CONOP, developed by RAND in 1994, is a time-dynamic model with a robust geographical representation much like THRUPUT2 and with features to handle intra-theater cargo lift and aerial refueling. CONOP was used to address force deployment policies relating to tanker aircraft and C-17 usage. NRMO, while developed and written from scratch, merged many of the techniques developed in the above mentioned models. (Melody, et al, 1997, p. 5) NRMO and its progenitors are all implemented with the Generalized Algebraic Modeling System (GAMS). [Brooke, Kendrick and Meeraus, 1988.]

3. Features

NRMO is a linear program. The objective function's primary purpose is to maximize on-time deliveries, air-asset measures of performance and ground assets measures of perfromance (Melody, et al., 1997, p.12). Mathematically, this is done through the minimization of the weighted sum of late and undelivered cargo penalties, subject to restrictions such as aircraft balance, aircraft payload, and airfield capacity (Baker, 1997, p. 55). There are secondary terms in the objective function, relating to preservation of assets, used to break ties among alternate optima with respect to the primary purpose. It can have up to twenty-seven

types of decision variables, which it uses to allocate aircraft and crews among various allowable options defined in terms of load carried, route and method of delivery.

NRMO's many features can be used to represent the complexities of an air mobility network (Melody, et al, 1997, p.10). NRMO's network representation allows for multiple embarkation, debarkation and enroute airfields, to include use of recovery bases (bases where aircraft are serviced following a quick turn-around mission). NRMO has the ability to add aircraft during the deployment period in order to simulate the mobilization of assets, such as Civilian Reserve Air Fleet (CRAF). Aircraft can be utilized in dual roles (ie. KC-10's can carry cargo or perform aerial re-fueling) and can, if needed, change roles during the execution of the model. In addition to inter-theater movement, NRMO can move cargo via intra-theater shuttles. NRMO also has the ability to track the movement of individual Time Phased Force Deployment Data (TPFDD) line numbers. (Melody, et al, 1997, p. 10)

4. Organization

NRMO consists of a GAMS formulation, five input files and an output report. The actual GAMS code for the original NRMO is not reproduced in this paper, but the conceptual formulation is shown in Figure 2:

Maximize: On-time Deliveries

          + air assets measure of performance

              + ground assets measure of performance

Subject to:

Meet time-phased demands:	by line id, cargo type
Aircraft Allocation/balance: strategic,	by type, airfield, for
missions	tanker, and tactical
Cargo Transshipment balance: time	by line id, cargo type.
Cargo/passenger capacity: time	by line id, aircraft type,
Aircraft utilization rates:	by aircraft type, time

Figure 2. Conceptual Formulation for NRMO. Although the conceptual formulization calls for maximization, this is actually accomplished by minimizing the weighted sum of late and undelivered cargo penalties (Melody, et al, 1997, p. 12)

NRMO's five input files contain all the information required for NRMO to solve the problem. Their contents are detailed in Appendix B. NRMO's output file is designed to be read as comma-delineated input to a spreadsheet. Its contents are also detailed in Appendix B.

5. Software

NRMO uses the Generalized Algebraic Modeling System (GAMS) [Brooke, et al, 1988]. GAMS is a commercial programming language specialized for linear, integer and non-linear programming. It is designed to allow models to be solved on many different types of computers with no formulation changes. GAMS requires no special editor or graphical user

interface, but instead can be written using any word processor. Hardware specifications call for 2MB RAM and 200KB Real Mode Memory to run GAMS, however an average sized NRMO scenario (single MTW) normally requires 250 to 300 megabytes of memory. Depending on the type of problem being solved, a GAMS user can choose from multiple solvers, seven of which can solve linear programming problems.

6.   Input

NRMO works in accordance with user-set delivery windows, defined in the input files by available-to-load dates, required delivery dates and maximum allowable late dates. While specific inputs will obviously vary from scenario to scenario, the following generic information is needed for NRMO to run a scenario:

a. Unit Movement Requirements: available-to-load dates, required delivery dates, commodity codes (a standard description of generic unit types that lets planners know how much of a certain type of a specific unit's cargo an aircraft can carry), and the actual number of passengers, and tons and types of cargo that need to be moved.

b. Route Data: bases and aircraft/route compatibility.

c. Base Data: location, MOG capacity, and specific use plans (off-load, recovery, tanker bed down, etc.)

d. Fleet Availability Data, by day.

e. Aircraft Data: speed, fuel consumption and payload.

7. Solution Method

NRMO's objective combines penalties for violating delivery schedules or cargo demands with penalties for actions that are wasteful or disrupt the smooth flow of operations. The major penalties are associated with personnel and cargo that are delivered late or not delivered at all. Secondary penalties are incurred for deadheading crews or for reassignment of aircraft from cargo to aerial refueling duties or vice versa. Finally, a reward can be earned for resting aircrews at bases that are embarkation nodes.

Optimization is done subject to the constraints shown in the conceptual formulation. The actual mathematical algorithms used to solve the problem will depend on the choice of solver. (Melody, et al, 1997, p. 33)

8. Results

Results from NRMO are applicable to analysis of airlift force structure, infrastructure and concepts of operations. Because the model uses available assets in the most efficient manner, shortfalls in meeting deployment requirements indicate a shortage of capability vice an inefficient scheduling heuristic (Melody, et al, 1997, p. 14). Airlift force structure sensitivity analysis can be accomplished by varying input data. Additional airlift force structure questions can also be answered through minor changes to the objective function. One example of this would be to let the initial aircraft inventory vary at a cost, so NRMO can "buy" the aircraft it needs to complete the mission. Similar analysis can be done on base infrastructure. Bases that are constrained by aircraft parking or fuel available can be quickly identified. This could answer the question of which bases would benefit most from augmentation of expeditionary airfield assets. Insight into questions like these can also be gained using the marginal values on constraints in the GAMS output.

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C.   MOBILITY OPTIMIZATION MODEL (MOM)

1.   Overview

Of the mobility models in NRMO's direct genealogy, the only one that included both air and sea components was the Mobility Optimization Model (MOM). MOM was developed to support the Mobility Requirements Study (MRS), that was mandated by Congress in the National Defense Authorization Act for Fiscal Year 1991. The purpose of MRS was to provide Congress with a plan for force projection in the 21st Century. During the course of MRS, it became evident that no adequate models for analysis of lift assets required to deploy forces were available. While some models could be used to identify shortfalls in capabilities, none could be used to identify how to overcome them. (Wing, et al, 1991, p. 2)

MOM was designed to solve two problems. The first (Phase I of the model), was to determine the minimum cost mix of lift assets needed to achieve on time delivery and sustainment of forces. The second (Phase II of the model) was to determine what affect an inadequate mix of assets would have on on-time delivery for a deployment. Used together, this would allow planners to find an optimal lift mix based on a most likely scenario (Phase I) and then see how it, or a less optimal mix, would work for other possible scenarios (Phase II) (Wing, et al, 1991, p. 3). MOM was modeled as a multi-commodity network flow problem, designed to be solved by linear programming. It was implemented in GAMS on a personal computer (Wing, et al, 1991, p. 20).

2.   Organization

The formulation for MOM Phase I has five parts; the inventory problem, demand satisfaction, air and sea throughput constraints, land and sea-based prepositioning and the objective function (Wing, et al, 1991, p. 5). The inventory problem is defined as what assets are available for each mission on a daily basis. Constraints on this problem come from lift asset

allocation and cycle time, with cycle time being the total time a lift asset requires to load, transit to the theater, off-load and return to the U.S. To simplify this process, MOM aggregated all U.S. bases into a single source node and all terminal destinations into a single sink node (Wing, et al, 1991, p 6). This gave reasonable approximations for airlift, but required the addition of delay variables for sealift, based on the fact that most men and equipment that require sea-transportation must be moved from home base to their POE and from their POD to their eventual destination.

Demand satisfaction means that the capacities of the lift assets multiplied by the number of lifts, summed over all lift assets during the allowed period to move a given unit, must equal the unit requirement for that commodity (Wing, et al, 1991, p 8). Demand satisfaction constraints ensure that the lift asset's capabilities, multiplied by the number of lifts and summed over all assets, equals the unit requirement for each commodity. Constraints are repeated for all types of cargo. This process was again simplified through aggregation, which was done across cargo categories using unit composition and lift asset capability. MOM then used a weighted average capacity for each lift asset, given the type of unit that was to be moved. (Wing, et al, 1991, p. 8)

Air and sea throughput constraints simply impose limits on the number of aircraft and ships that can arrive in theater, based on theater capacity. This constraint was not imposed on the Continental United States (CONUS), as it was felt the port and airfield system in the U.S. had a large enough capacity that limitations would not be a factor. (Wing, et al, 1991, p. 10)

Prepositioning was handled by MOM as either an input or a decision variable. MOM accounted for the increased efficiency in the careful loading of prepositioned equipment vice the

more hasty loading performed during a crisis, and also allowed for the return of ships to regular sea-lift duties once their prepositioned cargo had been delivered. (Wing, et al, 1991, p. 10)

The Phase I objective function minimized the sum of the cost of new lift assets and prepositioning assets. This allowed Phase I to answer the question of what was the minimum cost and asset mix to ensure delivery and sustainment of forces throughout a given scenario.

Phase II of MOM was designed to determine the best delivery schedule that an inadequate force of lift assets could make. Penalties were assessed for late or undelivered cargo and the objective function sought to minimize these penalties.

3.   Strengths and Limitations

MOM's strength was not only that it considered air and sealift, but also the prepositioning of cargo. The inclusion of prepositioning was especially useful, as this was the first model that included use of prepositioning as a strategic lift option (Wing, et al, 1991, p. 20). Another strength was the capability to model sustainment demand. MOM kept a count of the number of troops in theater and based the demand requirements on that number. One of MOM's perceived limitations was its high level of aggregation (Wing, et al, 1991, p. 21). Simplicity of the model was traded for model resolution. In addition to the aggregation of bases and cargo types, combat units were deployed at the brigade, group and corps levels. In reality, since MOM was designed to forecast the lift assets needed to complete a major deployment, this level of aggregation was appropriate. A second perceived limitation is the fact that MOM is scenario dependent (Wing, et al, 1991, p. 270). Any change in the scenario requires an equivalent change in data, which makes the analysis of different scenarios somewhat cumbersome. This "limitation", however, is certainly not unique to MOM. Many of the ideas from MOM were incorporated into NRMO, as will be seen later.

D. MODEL FOR INTERTHEATER DEPLOYMENT BY AIR AND SEA (MIDAS)

1. Overview

Another model that considers both air and sea components, and is still in use, is the Model for Intertheater Deployment by Air and Sea (MIDAS) (MIDAS UM, 1997). MIDAS was developed by the General Research Corporation (GRC) for the Projection of Forces Division of the Office of the Director of Program Analysis and Evaluation, within the Office of the Secretary of Defense [OD(PA&E)(PF)] (MIDAS UM, 1997, p. 1-3). MIDAS is a strategic deployment model that is used to analyze airlift, sealift and prepositioning options and can be operated as an integrated part of other systems or as a stand alone model. The current version, MIDAS 2.5, is written in C++ and runs on Sun workstations.

2. Data Management

The input data for MIDAS is similar to other models. There are three required input files, as well as additional files that can be used as appropriate. As with FDE, MIDAS files generally use a high level of aggregation; for example, the entire CONUS may be modeled as having only West Coast, East Coast and Gulf ports (Schank, et al, 1991, p. 61).

MIDAS output can include up to seven separate reports, covering ship and aircraft usage and movement, port and airfield throughput, load efficiency, and excesses and shortfalls of delivery of personnel and cargo. Because these reports are not available until the completion of the simulation, MIDAS also writes a stream of output while it executes. This output allows the user to follow the simulation throughout the execution. (MIDAS UM, 1997, p. 5-1)

3. Methodology

MIDAS uses heuristic scheduling algorithms to select modes of deployment for personnel and cargo, with the goal of finding a satisfactory, rather than optimal solution. MIDAS considers five deployment objectives:

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1. Efficient use of airlift and sealift transportation resources.

2. Timely delivery of forces.

3. Arrival of forces in sequential order, as defined by required delivery date (RDD).

4. Arrival of supplies in time to sustain already deployed forces.

5. Preservation of unit integrity.

MIDAS ranks these objectives in the order shown and will work to achieve the higher priority objectives at the expense of the lower (MIDAS UM, 1997, p. 2-1). While the ordering of these objectives is certainly reasonable in the sense of what MIDAS is used to analyze, from a real world viewpoint it seems unlikely that any commander would be willing to trade the efficient use of assets for the timely delivery of his forces.

MIDAS uses an adaptive scheduling approach. Once the deployment problem is solved, MIDAS executes that solution. After a period of time, MIDAS builds a new problem based on an updated status of resources, then solves and executes the new problem. This process is repeated until the deployment is complete. (MIDAS UM, 1997, p. 2-3)

Actual scheduling of assets is done by using the RDD's. Unlike other models, however, MIDAS does not schedule movements to meet RDD's, but rather uses the RDD's to set priorities. Cargo is then assigned to the mode of transportation that will get it to its destination in the shortest amount of time. Mode assignment can be changed as the scenario develops, i.e. if a faster type of transportation becomes available before a load of cargo is underway, MIDAS will re-schedule the cargo to load on the faster asset. (MIDAS, UM, 1997, p. 2-2)

4. Scheduling Heuristics

When ships are mobilized, they are assigned to a port of embarkation. As cargo becomes available for loading at that port, MIDAS looks at empty ships, ships that are currently loading and ships that are scheduled to load in the future. Also considered is the minimum

amount of cargo that a ship must carry before it will go to a port of debarkation. A ship that meets the minimum load requirement, can load all the given cargo and can deliver that cargo by the earliest date is selected and loaded. Partially loaded ships are given preference over empty ships. (MIDAS UM, 1997, p. 2-5)

Aircraft loading is accomplished in the same way, within constraints on aircraft productivity and airfield throughput. Also critical is the selection of aircraft routes. Viable routes are determined using the range-payload data of the aircraft, which shows how far an aircraft can fly based on what payload it is carrying. MIDAS ranks all possible routes using flow rates, which are determined by dividing the payload of the aircraft by the time required to complete the mission. The route with the most favorable (lowest) flow rate is considered the "best" route. If, however, the best route is not available and an alternate route that adds less than one day of travel is available, the alternate route will be chosen. (MIDAS UM, 1997, p. 2-5)

5.   Sustainment and Logistics

Like MOM, MIDAS also has the capability to dynamically generate sustainment demands for the deploying units. MIDAS tracks the daily inventory of each type of sustainment in the supply pipeline. As the deployment is executed, MIDAS calculates sustainment demand, based on consumption rates and the number of personnel in theater. If demand cannot be satisfied by present inventory, a sustainment requirement will be generated. These requirements are normally delivered by ship; however, if current stocks are exhausted and demand cannot be meet by sealift, the sustainment requirements will be moved by air. This is commonly referred to as a "greedy" or "myopic" heuristic.

III. CHANGES TO NAVAL POSTGRADUATE SCHOOL / RAND MOBILITY OPTIMIZER (NRMO)

A. METHODOLOGY

NRMO was written strictly as an airlift model. In order for it to be useful to J-8/WAD and comparable to FDE, however, it must also handle sealift. This additional capability required several augmentations to the existing NRMO model. In all cases, changes mimicked existing code in order to minimally affect the initial model. The result is the Naval Postgraduate School / RAND Mobility Optimizer, Air / Sea (NRMOAS), a version of NRMO with the necessary additions to allow the model to conduct both airlift and sealift operations. These additions mainly took the form of the additional sets required to allow NRMOAS to construct two networks: one for aircraft and one for ships. The two networks then required the addition of two sealift-only constraints, where a single joint constraint would not function logically. Finally, additions were made to the output report to accommodate a J-8 specific requirement. All changes are detailed in the remainder of the chapter. The full mathematical formulation for NRMOAS is also included.

B. ADDITIONAL SETS AND CONSTRAINTS

NRMO has the ability to represent an extensive and complicated air network. In order to allow NRMOAS to set up both an air and sea network, it was necessary to add sets to distinguish airfields from ports, aircraft from ships (referred to jointly as "vehicles"), and airports of embarkation (APOEs) from seaports of embarkation (SPOEs). These additions also required the separation of the variables used to make initial allocation of vehicles to embarkation nodes, thus ensuring that ships were not sent to APOEs and aircraft were not sent to POEs. Once initially allocated, ships travel only on sea routes and aircraft only on air routes,

so all other constraints can be used by both aircraft and ships without fear of redundant or conflicting use of assets.

Other changes that were required dealt with port capacity and fuel consumption constraints. NRMO uses the concept of maximum aircraft on ground (MOG) to determine airfield capacity. MOG is defined as the number of aircraft that an airfield can simultaneously service. It is calculated as a function of available aircraft parking spaces multiplied by an efficiency factor that reflects available airfield services and approximates the effects of congestion (queueing). (Goggins, Sept, 1995) NRMO uses two sizes of aircraft to calculate aircraft parking; narrow body (nb) and wide body (wb). All calculations use narrow body aircraft as the base. Similar to MOG, port berthing capacity is based on ship length, so when calculating port berthing, NRMOAS uses a similar simplified size comparison for ships. Small ships (ss) are defined as 800 feet or under in length, and large ships (ls) are defined as over 800 feet in length. The equations which calculate ship berthing and aircraft parking are then simply mirrors of each other. This leaves NRMOAS with two similar sets of capacity constraints, MOG for aircraft and port capacity for ships. In the case of an air / sea aggregate base, these separate calculations allow the MOG constraint to account for both aircraft parking and ship berthing without allowing either vehicle to use the other's available parking.

C.   CHANGES TO OUTPUT FILE

One J-8/WAD requirement was that the model allow the user to track the by-day delivery of every unit's cargo and personnel. NRMO did not include this data in its output file. The addition of a parameter to calculate this value, and an additional loop in the output generator to print the results easily accomplished this and also demonstrated the versatility of the output generator in accommodating user needs. In addition, a set was added to allow the

user to assign unit designators to line entries on the TPFDD. This makes the delivery reports easier to use when tracking unit deliveries. It is important to note that the addition of actual unit designations to deployment routes makes the data set used classified.

D. DATA COLLECTION

The biggest challenge to adding a sealift component to NRMO was collecting and inputting the data needed to allow NRMO to use ships. Every effort was made to draw data from FDE's database, so as to give a more valid comparison. Since NRMO's aircraft data was very complete, the main challenge lay in collecting and verifying the ship data. The Military Sealift Command (MSC), when fully mobilized, has access to 1066 ships, under both U.S. and allied registry. As with aircraft, the vast degree of variability from ship to ship makes a high degree of aggregation desirable. FDE uses five composite ship types. These ship types and their definitions are shown below and were used in NRMOAS.

Breakbulk (BB) – Ships in which cargo is loaded in holds

Fast Sealift (FSL) – Converted container ships. They are the largest and fastest

ships in the strategic sealift force. Their mission is rapid transport

of Army unit equipment

Lighter Aboard Ship (LASH) – Carries barges that are floated aboard and stacked

in slots. Similar in concept to stacking bakery trays in large

metal rack.

Roll On/ Roll Off (RORO) – Allow vehicles to "Roll On" and "Roll Off"

Large Medium Speed RORO (LMSR) – Self Explanatory

Values for ship speed, capacity, load and unload times and fuel consumption were taken directly from FDE. Where information was unavailable, it was developed from military manuals, phone calls and existing data sets. Additional data also had to be collected for the load capacities of various aircraft and ships. A vehicle's load capacity varies from unit to unit. The differences are most noticeable with over-sized and out-sized cargo, which are more limited by cubic size than by weight. NRMO's load capacity tables dealt only with aircraft. Similarly, FDE's capacity tables, while dealing with both aircraft and ships, were divided so that some units went solely by air and others went solely by sea (with the exception of personnel, which always travel by air). To allow NRMOAS the ability to send units by air or by sea (see section on Mode selection), load capacity tables were formed as a composite of those found both in NRMO and FDE. These composite tables were not used in every model run, as will be explained in the chapter dealing with the model comparisons.

E.   MODE SELECTION

NRMOAS operates with two types of travel mode selection; user designated and model designated. If the user desires to designate the mode of travel for a a unit, he or she simply designates that unit's embarkation node as an APOE or a POE. For example, if Dover Air Force Base is designated as an APOE, any unit embarking from there can only travel by air. If, however, a user wants NRMOAS to decide the most efficient mode of travel for a unit, the user must designate that unit's origin as both an APOE and a POE. This requires the creation of air / sea aggregate bases, that can accommodate both aircraft and ships. For example, a unit could depart from a North Carolina Air / Sea base that aggregates Pope Air Force Base and the port of Wilmington. NRMOAS would then determine whether the unit travels by air, sea, or a

combination of both. NRMOAS can also be used in a combined fashion, where the user designates the mode for some units and the model determines the mode for the others.

F.   NRMOAS FORMULATION

(Note: This formulation is adapted from the NRMO formulation found in the reference Melody, et al, 1997. Much of the formulation is reproduced with no change. Sets that have been added and constraints that were altered for NRMOAS are noted in bold type.)

Indices

a	vehicle type
b	base
c	cargo type
i	line id
r	route
t	time period

Note: In some cases, subscripts other than indices are used to indicate subsets.

Sets

T	time periods
TWi	delivery time window for line id i
T_u	set of time periods associated with a ute rate constraint block, u
FT	flow time periods, f = {1,...,maximum mission time}
U	utilization rate enforcement blocks
I	line id's
I_{fob}	subset of line id's whose destination is a FOB
$I_{apd} = I/I_{fob}$	subset of line id's whose destination is a APOD
$I_{b,dst}$	subset of line id's that have base b (FOB or APOD) as a destination
$I_{b,trn}$	subset of line id's that have base a (an APOD) as a transhippment point
$I_{b,sup}$	subset of line id's whose destination is in the theater belonging to super node sup
C	cargo types {bulk, over, out, pax}
CC	cargo types {bulk, over, out}
C_a	subset of cargo types that can be carried by vehicle type a
A	set of vehicle types
A_{acft}	**subset of vehicle types that are aircraft**
A_c	subset of vehicle types that can carry cargo type c
A_{mix}	subset of vehicle types that can carry pax and at least one other cargo type {bulk, over, out}
A_{pax}	subset of vehicle types that can carry passengers
A_{ship}	**subset of vehicle types that are ships**

A_{tkr}	subset of tanker aircraft types
A_{rfl}	subset of vehicle types that can be refueled by a tanker
A_{chp}	subset of vehicles that can be "chopped"
B	set of all "bases" (APOE,APOD,FOB,super,enroute,waypoint,beddown, aerial refueling points or ports)
B_{sup}	subset of bases that are supernodes
B_{af}	**subset of bases that are airfields**
B_{port}	**subset of bases that are ports**
B_e	subset of bases that are embarkation nodes
B_{apoe}	**subset of embarkation nodes that are air embarkation nodes**
B_{spoe}	**subset of embarkation nodes that are sea embarkation nodes**
B_{arp}	subset of bases that are AR points
B_{tkr}	subset of bases that are beddown bases for tankers
BS_{rec}	set of super nodes that have at least one recovery base
B_{way}	set of bases that are enroute navigational waypoints
$BS_{b,dwn}$	set of super nodes that have b as a shuttle beddown node
$BS_{b,sup}$	set of FOB's that call b their super node plus the super node itself
$BA_{b,tkr}$	subset of B_{arp} that are served by $b \in B_{tkr}$
$BT_{b,arp}$	subset of B_{tkr} that serve $b \in B_{sup}$
B_{crw}	crew stage bases

Routes

R	set of all routes
RD	subset of routes that are delivery routes
RB	subset of routes that are backchannel routes
RB_{rec}	subset of backchannel routes that include a recovery base
RD_b	delivery routes that use base b (terminal node is a super, not FOB or APOD)
$RD_{ia,dir}$ delivery	subset of routes that can be traveled by a vehicle of type a and carry i for direct delivery
RB_{ab}	subset of backchannel routes that use b and can be traveled by a vehicle of type a
$RD_{b,div}$	set of delivery routes that have b as a divert base
$RB_{b,div}$	same for backchannel routes
$R_{b,ori}$	routes whose origin is base b
$R_{b,dst}$	routes whose destination is base b

Data

Mission time data

$rtrv_{ar}$	total travel time for vehicle a to travel on route r (periods)
trv_{ar}	rounded $rtrv_{ar}$ (integer periods)
$retrv_{abr}$	travel time for vehicle a to reach base b when traveling route r (periods)
$etrv_{abr}$	rounded $retrv_{abr}$ (integer periods)

$maxtrv_a$	maximum travel time along any route for vehicle a (integer periods)
$msntime_{arf}$	time flown f periods into a mission (hours), where f is a time period used to calculate flight hours

- $hrsper$ if $rtrv_{ar} > f$ (mission continues throughout its f th period)
- 0 if $rtrv_{ar} \leq f\text{-}1$ (mission terminates before its f th period)
- $hrsper \cdot (rtrv_{ar} - (f\text{-}1))$ if $f\text{-}1 \leq rtrv_{ar} \leq f$ (mission terminates during its f th period)

$flttime_{arf}$	same as $msntime_{arf}$, but only includes actual travel time, thus, $flttime_{arf} < msntime_{arf}$, since all missions have some ground or port delay time
$gtime_{abr}$	ground or port delay time for vehicle a at base b when traveling route r (hrs)
$qtime_{abr}$	offload time for vehicle a at base b when traveling route r when recovery used (hrs)
$ctrvabr$	travel time to b, plus crew rest, for a along r (integer periods)
$cttrv_{ab}$	$ttrv_{ab}$ plus crew rest (integer periods)
$dhtrv_{b'b}$	travel time for deadheading crew from b' to b (integer periods)
$rttrv_{ab}$	tanker a reposition time (approx 2 days) from embarkation or beddown base b to cloud
$ttrv_{ab}$	rounded $rttrv_{abr}$ (integer periods)
$tkrtime_{abb'}$	in-flight time for tanker a flying from b to b' and back (UTE) (hrs)
$tkrrate_{abb'}$	maximum number of in-theater shutles per aircraft per period
$shutrate_{ai}$	maximum number of in-theater shuttles per aircraft per period
$gtrv_i$	in-theater ground travel time for i (periods)
$shuttime_{ia}$	shuttle travel time (for UTE) (hrs)

Vehicle data

$newv_{at}$	number of new vehicles of type a available in period t
cum_{at}	$= \sum_{t' \leq t} newv_{at'}$
$crewrat_a$	ratio of available crews to vehicle a
$purecap_{iac}$	number of stons of unit i's cargo of type c that can be loaded on vehicle type a
$maxpax_a$	maximum number of pax that can be loaded on vehicle type a
$paxfrac_a$	fraction of a vehicle's capacity that can be loaded with pax
$rangefac_{iar}$	fraction of vehicle available for loading when flying route r for line id i
$restrew_a$	unit reward for resting vehicle at base $b \in B_e$
	$(max_{ic} \{purecap_{iac}\} \cdot latepen_i \cdot 0.01)$
$usepen_a$	usage penalty for theater aircraft and tanker reassignments
$dhpen_a$	penalty for deadheading crews
$tkrprop_{abb'}$	proprotion of a full tanker consumed by aircraft a refueling at AR b on r (KC10 equiv)
$dpct_a$	fraction of AR attempts by aircraft a (the one getting the fuel) that fail
$urate_a$	number of hours per day that vehicle a can operate
$initchop_{ab}$	initial vehicles chopped to theater

Movement requirements data

rdd_i	required delivery date
dem_{ic}	stons of demand for line id i of type c
$latepen_i$	late delivery penalty for i per day per ston
$maxlate_i$	maximum number of time periods late delivery for line id i can arrive
$nogopen_i$	non-delivery penalty per ston ($\geq latepen_i \cdot maxlate_i$)

Other data and notational conventions

$hrsper$	number of hours per period
$acpkg_{ab}$	unit MOG consumption of vehicle a at base b
$mogeff_b$	MOG efficiency at b
mog_b	base capacity; service spot hours per period at b
$I(\cdot)$	1 if argument is true; 0 otherwise
$(x)^+$	$= \max\{0,x\}$
$\overline{S}$	complement of a generic set S

In general, constraints and variables indexed by t are assumed to exist only for the appropriate combinations of t with those other indices.

DECISION VARIABLES (all non-negative)

Vehicle mission variables

XD_{iart}	# of vehicles a direct delivering i on route r departing at time t
XT_{iart}	# of vehicles a delivering a transshipment load of i on route r departing at time t
XDR_{iart}	# of vehicles a direct delivering i on quick route r departing at time t
XTR_{iart}	# of vehicles a delivering a transshipment load of i on quick turn route r departing at time t
XS_{iat}	# of (Round trip) shuttle missions by vehicle a delivering i in t
Y_{art}	# of vehicle a recovering on route r departing at t
$TKRA_{abb't}$	# of tanker sorties of type a flown from $b \in B_{tkr}$ to $b' \in B_{arp}$ in t

Vehicles inventory variables

$RONAPOE_{abt}$	**# of aircraft a remaining over night at $b \in B_e$ in t**
$RONPOE_{abt}$	**# of ships a remaining over night at $b \in B_e$ in t**
$RONT_{abt}$	# of vehicles a "RONing" without recovery in t
$RONR_{abt}$	# of vehicles a "RONing" with recovery in t
$IRONR_{ab}$	# of vehicles a initially assigned to b (non-recovery)
$IRONR_{ab}$	# of vehicles a initially assigned to b (recovery)
$THCHOP_{abt}$	# of vehicles a assigned to super b's shuttle fleet from non-recovery routes in t
$THCHOPR_{abt}$	# of vehicles a assigned to super b's shuttle fleet from

	recovery routes in t
$TKRB_{abt}$	# of tankers a whose beddown base is $b \in B_{tkr}$ in t

Vehicles changing roles

$ALLOCACFT_{abt}$	**# of new aircraft allocated to $b \in B_{apoe}$ in t**
$ALLOCSHIP_{abt}$	**# of new ships allocated to $b \in B_{poe}$ in t**
$TKREC_{abt}$	# of tankers a leaving $b \in B_e$ in t for service as a re-fueler (for cloud)
$TKRCE_{abt}$	# of tankers a leaving tanker fleet (cloud) in t for $b \in B_e$ for cargo hauling
$TKRBC_{abt}$	# of tankers a assigned a super b's shuttle fleet from non-recovery routes
$TKRCB_{abt}$	# of tankers a being reassigned (from cloud) in t to $b \in B_e$ for refueling

Cargo

$DTONS_{iact}$	stons of i's cargo of type c direct delivered by a that will arrive in t
$TTONS_{iact}$	stons of i's cargo of type c for transshipment by a arriving at (the transshipment node) in t
$STONS_{iact}$	stons of i's cargo of type c shuttled by a in t
$GTONS_{ict}$	stons of i's cargo of type c ground that will arrive at the FOB in t
$NOGO_{ic}$	stons of i's cargo of type c not delivered

Crews

$SCREWS_{abt}$	# of crews available (rested) for a at $b \in B_{crw}$ at the beginning of time t
$DHCREWS_{ab'bt}$	# of deadheadiing crews for a leaving b' at time t for reassignment to b

OBJ: Objective Function

$$\sum_{i \in I} \sum_{a \in A} \sum_{c \in C_a} \sum_{t \in TW_i} latepen_i \cdot (t - rdd_i)^+ \cdot DTONS_{iact}$$

$$+ \sum_{i \in I_{fob}} \sum_{a \in A} \sum_{c \in C_a} \sum_{t \in TW_i} \cdot (t - rdd_i)^+ \cdot STONS_{iact}$$

$$+ \sum_{i \in I_{fob}} \sum_{c \in C} \sum_{t \in TW_i} nogopen_i \cdot (t - rdd_i)^+ \cdot GTONS_{ict}$$

$$+ \sum_{i \in I} \sum_{c \in C} nogopen_i \cdot NOGO_{ic}$$

$$+ \sum_{a \in A_{chp}} \sum_{b \in B_{sup}} \sum_{t \in T} usepen_a \cdot [THCOP_{abt} + THCHOPR_{abt}]$$

$$+ \sum_{a \in A_{tkr}} \sum_{b \in B_e} \sum_{t \in T} usepen_a \cdot TKREC_{abt} + \sum_{a \in A_{tkr}} \sum_{b \in B_{tkr}} \sum_{t \in T} usepen_a \cdot TKRBC_{abt}$$

$$- \sum_{a \in A} \sum_{b \in B_e} \sum_{t \in T} restrew_a \cdot (RONAPOE_{abt} + RONPOE_{abt}) +$$

$$\sum_{a \in A_{tkr}} \sum_{b,b' \in B_{crw}} \sum_{t \in T} dhpen_a \cdot DHCREW_{abb't}$$

Minimize the sum of: (1) late penalty * number of days late * late cargo delivered directly to the line id's destination, (2) late penalty * number of days late * late cargo shuttled (from the transshipment base) to the line id's destination, (3) late penalty * number of days late * late cargo delivered by ground from the transshipment base, (4) nondelivery penalty * undelivered cargo, (5) usage penalty * chopped vehicles or reassigned tankers, (6) a small reward (negative penalty) * vehicles remaining overnight at an embarkation node (often CONUS, and thereby near home station), and (7) crew deadhead penalty * deadheading crews.

ACBALAPOE: Aircraft Balance at Air Embarkation Nodes (Change from NRMO)

$$\sum_{i \in I_{fob}} \sum_{r \in RD_b \cap RD_{ia,trn}} XT_{iart} + \sum_{i \in I} \sum_{r \in RD_b \cap RD_{ia,dir}} XD_{iart}$$

$$+ \sum_{i \in I_{fob}} \sum_{r \in RD_b \cap RD_{ia,trn}} XTR_{iart} + \sum_{i \in I} \sum_{r \in RD_b \cap RD_{ia,dir}} XDR_{iart}$$

$$+ I(a \in A_{tkr}) \cdot [TKREC_{abt}] + RONAPOE_{abt} = RONAPOE_{a,b,t-1} + \sum_{r \in RB_{ab}} Y_{a,r,t-trv_{ar}}$$

$$+ ALLOCACFT_{abt} + I(a \in A_{tkr}) \cdot [TKRCE_{abt}]$$

$$\forall a \in A_{acft}, b \in B_{apoe}, t \in T$$

Aircraft Balance at APOEs: For each aircraft type, APOE, and time period (day); departing transshipment missions + departing direct delivery missions + assignments to tanker duty (if aircraft is a tanker) + overnight resting aircraft = resting aircraft from yesterday + arriving backchannel missions + newly assigned aircraft + reassignments from tanker duty (if aircraft is a tanker). Note that direct delivery missions and transshipment missions can be selected to recover away from the APOD (XDR, XTR) or recover at the APOD (XD, XT) missions. This is true throughout the formulation, except as noted.

SHBALPOE: Ship Balance at Sea Embarkation Nodes (Change from NRMO)

$$\sum_{i \in I_{fob}} \sum_{r \in RD_b \cap RD_{ia,trn}} XT_{iart} + \sum_{i \in I} \sum_{r \in RD_b \cap RD_{ia,dir}} XD_{iart} + RONPOE_{abt}$$

$$= RONPOE_{a,b,t-1} + \sum_{r \in RB_{ab}} Y_{a,r,t-trv_{ar}} + ALLOCSHIP_{abt}$$

$$\forall \, a \in A_{ship}, \, b \in B_{poe}, \, t \in T$$

Ship Balance at SPOEs: Same for ACBALAPOE, but balances numbers of ships at POE's only. Note that ships will not be assigned to tanker duty.

VBALSUP: Vehicle Balance at SUPER Debarkation Nodes

$$\sum_{r \in RB_{ab} \cap RB_{rec}} Y_{art} + RONT_{abt} + THCHOP_{abt} =$$

$$\sum_{i \in I_{fob}} \sum_{r \in RD_b \cap RD_{ia,trn}} XT_{i,a,r,t-trv_{ar}} + \sum_{i \in I} \sum_{r \in RD_b \cap RDia,dir} XD_{i,a,r,t-trv_{ar}} +$$

$$RONT_{a,b,t-1} + THCHOP_{a,b,t-1} + I(t=1) \cdot IRON_{ab}$$

$$\forall \, a \in A, \, b \in BS_{sup}, \, t \in T$$

Vehicle Balance At Super Nodes: A "super" node is a surrogate for all bases in the theater. Flow balance is done with supers, but MOG is constrained at the actual theater POD's and FOB's. Additionally, this constraint only addresses missions that recover at the POD. Other missions are constrained in VBALREC. For each vehicle type, "super", and time period; the departing backchannel missions + overnightr resting vehicles + total vehicles chopped to the theater = arriving transshipment missions + arriving direct delivery missions (for those line id's whose destination is an POD) + last nights resting vehicles + yesterday's total of chopped vehicles + the initial "chops" to theater (if it the first time period).

VBALREC: Vehicle Balance at SUPER Debarkation Nodes

$$\sum_{r \in RB_{ab} \cap RB_{rec}} Y_{art} + RONR_{abt} + THCHOPR_{abt} =$$

$$\sum_{i \in I_{fob}} \sum_{r \in RD_b \cap RD_{ia,trn}} XTR_{i,a,r,t-trv_{ar}} + \sum_{i \in I} \sum_{r \in RD_b \cap RD_{ia,dir}} XDR_{i,a,r,t-trv_{ar}} +$$

$$RONR_{a,b,t-1} + THCHOPR_{a,b,t-1} + I(t=1) \cdot IRONR_{ab}$$

$$\forall\, a \in A,\, b \in BS_{rec},\, t \in T$$

Vehicle balance at super's using recovery routes: Same as VBALSUP, but balance flow for missions not recovering at the POD

INITRON: allocate initial chops to recovery or not

$$IRONT_{ab} + IRONR_{ab} = initchop_{ab} \qquad\qquad \forall\, a \in A_{chp},\, b \in B_{sup}$$

Initial RONS in theater: For period 1 and all vehicles and supers; the sum of RONS at POD recoveries + RONS at non-POD recoveries = initial aircraft chopped to theater.

ACFTALLOC: allocate newly available aircraft (Change from NRMO)

$$\sum_{b \in B_{apoe}} ALLOCACFT_{abt} = newv_{at} \qquad\qquad \forall\, a \in A_{acft},\, t \in T$$

Aircraft allocation: For each aircraft type and time period; the sum of all new allocations to APOE's = the amount newly available.

SHIPALLOC: allocate newly available ships (Change from NRMO)

$$\sum_{b \in B_{poe}} ALLOCSHIP_{abt} = newv_{at} \qquad\qquad \forall\, a \in A_{ship},\, t \in T$$

Ship Allocation: Same as ACFTALLOC, but for ships only.

SHUTLBND: don't send more tankers than available

$$\sum_{i \in I_{b,sup} \cap I_{fob}} \frac{XS_{iat}}{shutrate_{ia}} \le [THCHOP_{abt} + THCHOPR_{abt}]$$

$$\forall a \in A_{acft}, b \in B_{sup}, t \in T$$

Shuttle Bound: For each vehicle type, "super" pod, and time period; the number of round trip shuttle missions divided by the daily number of round trip missions per aircraft ≤ total chopped vehicles in the theater.

TKRBND: don't use more tankers than available

$$\sum_{b' \in BA_{b,tkr}} \cdot \frac{TKRA_{abb't}}{tkrrate_{abb'}} \le TKRB_{abt} \qquad \forall a \in A_{tkr'}, b \in B_{tkr'} t \in T$$

Tanker Bound: For all tankers, tanker beddown bases, and time periods; the number of AR sorties flown to all tracks divided by the daily sortie rate ≤ tankers assigned to the beddown base.

CLOUDBAL: flow balance; leaving and entering tanker fleet

$$\sum_{b \in B_{apoe}} TKREC_{a,b,t-ttrv_{ab}} + \sum_{b \in B_{tkr}} TKRBC_{a,b,t-ttrv_{ab}} =$$

$$\sum_{b \in B_{apoe}} TKRCE_{abt} + \sum_{b \in B_{tkr}} TKRCB_{abt} \qquad \forall a \in A_{tkr'} t \in T$$

Tanker Cloud Balance: The "tanker cloud" is an expression for the act of assigning or de-assigning multi-role aircraft as dedicated tankers. The "cloud" serves as a control point that reduces the number of required assignment and de-assignment variables. For all tanker aircraft types and time periods; newly assigned tankers from all APOE's (adjusted for travel time) + newly de-assigned tankers from all tanker beddown bases (adjusted for travel time) = tankers returning to all APOEs + tankers deploying to all beddown bases. Note that de-assigning a tanker from a beddown base does not force it back to an APOE, it could be re-assigned to another beddown base.

TKRINVT: tanker inventory at tanker beddowns

$$TKRBC_{abt} + TKRB_{abt} = TKRCB_{abt} + TKRB_{a,b,t-1} \quad \forall a \in A_{tkr}, b \in B_{tkr}, t \in T$$

Tanker Inventory: For all tankers aircraft types, tanker beddown bases, and time periods; newly de-assigned tankers + total tankers assigned = newly assigned tankers + total tankers assigned from last period.

ARMOG: aerial refueling capacity constraint

$$\sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_b \cap RD_{ia,dir}} tkreqvs_{abr} \cdot XD_{i,a,r,t-etrv_{abr}}$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl} \cdot} \sum_{r \in RD_b \cap RD_{ia,trn}} tkreqvs_{abr} \cdot XT_{i,a,r,t-etrv_{abr}}$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_b \cap RD_{ia,dir}} tkreqvs_{abr} \cdot XDR_{i,a,r,t-etrv_{abr}}$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_b \cap RD_{ia,trn}} tkreqvs_{abr} \cdot XTR_{i,a,r,t-etrv_{abr}}$$

$$\sum_{a \in A_{rfl}} \sum_{r \in RB_{ab}} tkreqvs_{abr} \cdot Y_{a,r,t-etrv_{abr}}$$

$$\leq \sum_{b' \in BT_{b,arp}} \sum_{a \in A_{tkr}} tkrprop_{ab'b} \cdot TKRA_{ab'bt} \quad \forall b \in B_{arp}, t \in T$$

Air Refueling MOG: Despite the apparent contradiction in terms, this constraint is the air refueling analog to airfield MOG. It constrains the capacity of an AR track. For all air refueling points and time periods; the fuel required by direct delivery, transshipment, and backchannel missions hitting the track in this time period ≤ the amount of fuel available by tanker sorties flown to the track.

UTE: utilization rate

$$\sum_{t \in T_u} \sum_{i \in I} \sum_{r \in RD_{ia,dir}} \sum_{f \in FT} flttime_{arf} \cdot XD_{i,a,r,t-(f-1)}$$

$$+ \sum_{t \in T_u} \sum_{i \in I_{fob}} \sum_{r \in RD_{ia,trn}} \sum_{f \in FT} flttime_{arf} \cdot XT_{i,a,r,t-(f-1)}$$

$$+ \sum_{t \in T_u} \sum_{i \in I} \sum_{r \in RD_{ia,dir}} \sum_{f \in FT} flttime_{arf} \cdot XDR_{i,a,r,t-(f-1)}$$

$$+ \sum_{t \in T_u} \sum_{i \in I_{fob}} \sum_{r \in RD_{ia,trn}} \sum_{f \in FT} flttime_{arf} \cdot XTR_{i,a,r,t-(f-1)}$$

$$+ \sum_{i \in I_{fob}} \sum_{t \in T_u} shuttime_{ia} \cdot XS_{iat} + \sum_{t \in T_u} \sum_{r \in RB_b} \sum_{f \in FT} flttime_{arf} \cdot Y_{a,r,t-(f-1)}$$

$$+ I(a \in A_{tkr}) \cdot \left[\sum_{b \in B_{tkr}} \sum_{b' \in B_{arp}} \sum_{t \in T_u} tkrtime_{abb'} \cdot TKRA_{abb't} + \right.$$

$$\sum_{b \in B_{apoe}} \sum_{t \in T_u} hrsper \cdot rttrv_{ab} \cdot TKREC_{abt} +$$

$$\left. \sum_{b \in B_{tkr}} \sum_{t \in T_u} hrsper \cdot rttrv_{ab} \cdot TKRBC_{abt} \right]$$

$$\leq \sum_{t \in T_u} cumac_{at} \cdot urate_a \qquad\qquad \forall a \in A_{acft}, u \in U$$

Utilization Rate: Sums all varieties of travel time, so the left-hand side of this constraint accumulates travel time only of missions operating during blocks of UTE rate enforcement (typically 10-20 day blocks). For each vehicle type and UTE rate block; the travel time of all direct, transshipment, shuttle, and backchannel missions (as well as deployed and deploying tankers, if appropriate) $\leq$ total vehicles available * maximum hours per day of average vehicle utilization. The f index corresponds to the number of days into a mission, so when $f = 1$, a typical term is the flight time of a mission's first day * the number of missions (of that type) launched that day. Similarly, when $f = 2$, a typical term corresponds to the flight time of a mission's second day * the number of missions (of that type) launched on the previous day.

VCONSUME: max vehicle usage to lessen rounding effects

$$\sum_{i \in I} \sum_{r \in RD_{ia,dir}} \sum_{f \in FT} msntime_{arf} \cdot XD_{i,a,r,t-(f-1)}$$

$$+ \sum_{i \in I_{fob}} \sum_{r \in RD_{ia,trn}} \sum_{f \in FT} msntime_{arf} \cdot XT_{i,a,r,t-(f-1)}$$

$$+ \sum_{i \in I} \sum_{r \in RD_{ia,dir}} \sum_{f \in FT} msntime_{arf} \cdot XDR_{i,a,r,t-(f-1)}$$

$$+ \sum_{i \in I_{fob}} \sum_{r \in RD_{ia,trn}} \sum_{f \in FT} msntime_{arf} \cdot XTR_{i,a,r,t-(f-1)}$$

$$+ \sum_{i \in I_{fob}} \frac{hrsper}{shutrate_{ai}} \cdot XS_{iat} + \sum_{r \in RB} \sum_{f \in FT} msntime_{arf} \cdot Y_{a,r,t-(f-1)}$$

$$+ I(a \in A_{tkr}) \cdot \Big[\sum_{b \in B_{tkr}} \sum_{b' \in B_{arp}} \frac{hrsper}{tkrrate_{abb'}} \cdot TKRA_{abb't} +$$

$$\sum_{b \in B_{apoe}} rttrv_{ab} \cdot hrsper \cdot TKREC_{abt} +$$

$$\sum_{b \in B_{tkr}} rttrv_{ab} \cdot hrsper \cdot TKRBC_{abt} \Big]$$

$$+ \sum_{b \in B_{apoe}} hrsper \cdot RONAPOE_{abt} + \sum_{b \in B_{poe}} hrsper \cdot RONPOE_{abt}$$

$$+ \sum_{b \in B_{sup}} hrsper \cdot \Big[RONT_{a \in A_{acft},bt} + RONR_{a \in A_{acft},bt} \Big]$$

$$\leq hrsper \cdot cumac_{at} \qquad\qquad \forall\, a \in A,\, t \in T$$

Vehicles Consumed: Structurally similar to UTE, this constraint reduces the effect of time discretization. It supplements the flow balance constraints, which may deal with short missions whose rounded duration is 0 periods. For all vehicle types and time periods; mission time of all direct, transshipment, shuttle, and backchannel missions (as well as deployed and deploying tankers, if appropriate) + resting aircraft $\leq$ total vehicle hours available.

DCAPACITY: direct delivery capacity

$$\sum_{c \in C_a \cap CC} \frac{DTONS_{iact}}{purecap_{iac}} + \frac{paxfrac_a \cdot DTONS_{i,a,pax,t}}{maxpax_a} \cdot I(a \in A_{pax})$$

$$\leq \sum_{r \in RD_{ia,dir}} rangefac_{iar} \cdot \left[XD_{i,a,r,t-trv_{ar}} + XDR_{i,a,r,t-trv_{ar}} \right] \quad \forall\, i \in I, a \in A, t \in T$$

Direct Delivery Mission Capacity: For each line id, vehicle type, and time period; the number of tons delivered (summed over cargo classes) divided by the vehicle capacity by cargo type and unit + the passengers delivered divided by the passenger capacity $\leq$ the number of missions launched in support of i by vehicle of type a along any route, launched long enough ago so as to be arriving at time t. $paxfrac$ specifies the portion of the vehicle filled if fully loaded with passengers. Parameter $rangefac$ is frequently 1, but is reduced if the critical leg is long enough to exceed the vehicle's range/payload performance.

TCAPACITY: transshipment delivery capacity

$$\sum_{c \in C_a \cap CC} \frac{TTONS_{iact}}{purecap_{iac}} + \frac{paxfrac_a \cdot TTONS_{i,a,pax,t}}{maxpax_a} \cdot I(a \in A_{pax})$$

$$\leq \sum_{r \in RD_{ia,trn}} rangefac_{iar} \cdot \left[XT_{i,a,r,t-trv_{ar}} + XDTR_{i,a,r,t-trv_{ar}} \right] \quad \forall\, i \in I_{fob}, a \in A, t \in T$$

Transshipment Mission Capacity: Same as DCAPACITY, but applies to missions flown in support of cargo and pax deliveries to transshipment POD's (for subsequent transshipment).

SCAPACITY: shuttle delivery capacity

$$\sum_{c \in C_a \cap CC} \frac{STONS_{iact}}{purecap_{iac}} + \frac{paxfrac_a \cdot STONS_{i,a,pax,t}}{maxpax_a} \cdot I(a \in A_{pax})$$

$$\leq srange_{ia} \cdot XS_{iat} \qquad \forall\, i \in I_{fob}, a \in A, t \in T$$

Shuttle Mission Capacity: Same as DCAPACITY and TCAPACITY, but applies to intra-theater missions moving cargo from transshipment POD's to FOB's.

DPAXCAP: direct delivery of pax

$$DTONS_{i,a,pax,t} \leq$$

$$\sum_{r \in RD_{ia,dir}} \max pax_a \cdot \left[XD_{i,a,r,t-trv_{ar}} + XDR_{i,a,r,t-trv_{ar}} \right] \quad \forall i \in I, a \in A_{mix}, t \in T$$

Direct Delivery Mission Pax Capacity: For each line id, vehicle type, and time period; the number of pax moved must not exceed the maximum pax per mission * number of missions executed. It supplements DCAPACITY, which would (by itself) allow for aircraft to be fully loaded with pax, despite available seating configurations. **NOTE**: *DTONS, TTONS*, and *STONS* represent number, not tons of pax.

TPAXCAP: delivery of pax for transshipment

$$TTONS_{i,a,pax,t} \leq$$

$$\sum_{r \in RD_{ia,tm}} maxpax_a \cdot \left[XT_{i,a,r,t-trv_{ar}} + XTR_{i,a,r,t-trv_{ar}} \right] \quad \forall i \in I_{fob}, a \in A_{mix}, t \in T$$

Transshipment Mission PAX Capacity: Same as DPAXCAP, but applies to transhippment missions.

SPAXCAP: delivery of pax by shuttles

$$STONS_{i,a,pax,t} \leq maxpax_a \cdot XS_{ait} \quad \forall i \in I_{fob}, a \in A_{mix}, t \in T$$

Shuttle Mission PAX Capacity: Same as DPAXCAP and TPAXCAP, but applies to intra-theater shuttle mission.

MEETDEM: meet demand for each line id

$$\sum_{a \in A_c} \sum_{t \in T} DTONS_{iact} + NOGO_{ic}$$

$$+ I(i \in I_{fob}) \cdot \left[\sum_{a \in A_c} \sum_{t \in T} STONS_{iact} + \sum_{t \in T} GTONS_{ict} \right] = dem_{ic} \quad \forall i \in I, c \in C$$

Meet Demand: For each line id and cargo class; direct delivery tons (and pax) moved by all vehicles over the available time window + tons moved by shuttle missions (if destination is a FOB) + tons moved by ground (if destination is a FOB) + cargo NOT moved = demand by unit and cargo class.

TRANSTONS: flow balance for transshipped stons

$$\sum_{a \in A_c} TTONS_{iact} = \sum_{a \in A_c} STONS_{iact} + GTONS_{i,c,t+gtrv_i} \quad \forall\, i \in I,\, c \in C,\, t \in T$$

Transshipment Tons: For each line id, cargo class and time period: transshipment tons moved by strategic lift = tons moved to FOB by shuttle or ground transport.

INITCREWS: initialize crew placement

$$\sum_{b \in B_{crw}} SCREWS_{abt} + crewrat_a \cdot \sum_{b \in B_{tkr}} TKRB_{abt} = crewrat_a \cdot newac_{at} \qquad \forall\, a, t = 1$$

Initialize Crews: For all vehicles and time period 1; strategic lift crews available at all crew stage bases + crew contingent for all pre-deployed tankers = number of crews available.

SCREWBAL: strategic crew balance of flow

$$
\begin{aligned}
SCREWS_{abt+1} = \ & SCREWS_{abt} \\
& + \sum_{i \in I} \sum_{r \in RD_{ia,dir} \cap \bar{R}_{b,ori}} \left[XD_{i,a,r,t\text{-}ctrv_{abr}} + XDR_{i,a,r,t\text{-}ctrv_{abr}} \right] \\
& + \sum_{i \in I_{fob}} \sum_{r \in RD_{ia,trn} \cap \bar{R}_{b,ori}} \left[XD_{i,a,r,t\text{-}ctrv_{abr}} + XDR_{i,a,r,t\text{-}ctrv_{abr}} \right] \\
& + \sum_{r \in RB \cap \bar{R}_{b,ori}} Y_{a,r,t\text{-}ctrv_{abr}} - \sum_{i \in I} \sum_{r \in RD_{ia,dir} \cap \bar{R}_{b,dst}} \left[XD_{i,a,r,t\text{-}etrv_{abr}} + XDR_{i,a,r,t\text{-}etrv_{abr}} \right] \\
& - \sum_{i \in I_{fob}} \sum_{r \in RD_{ia,trn} \cap \bar{R}_{b,dst}} \left[XT_{i,a,r,t\text{-}etrv_{abr}} + XTR_{i,a,r,t\text{-}etrv_{abr}} \right] \\
& - \sum_{r \in RB \cap \bar{R}_{b,dst}} Y_{art\text{-}etrv_{abr}} + I(b \in B_{apoe}) \cdot crewrat_a \cdot \left[TKRCE_{a,b,t\text{-}cttrv_{ab}} - TKREC_{abt} \right] \\
& + I(b \in B_{sup}) \cdot crewrat_a \cdot \left[THCHOP_{a,b,t\text{-}1} - THCHOP_{abt} + I(t = 1) \cdot IRONT_{ab} \right] \\
& + I(b \in BS_{rec}) \cdot crewrat_a \cdot \left[THCHOPR_{a,b,t\text{-}1} - THCHOPR_{abt} + I(t = 1) \cdot IRONR_{ab} \right] \\
& + I(b \in B_e,\, t \neq 1,\, newac_{at} > 0) \cdot crewrat_a \cdot (ALLOCACFT_{abt} + ALLOCSHIP_{abt}) \\
& + \sum_{b' \in B_{crw}} DHCREW_{a,b',b,t\text{-}dhtrv_{b'b}} - \sum_{b' \in B_{crw}} DHCREW_{abb't} \qquad \forall\, a \in A_{acft},\, b \in B_{crw},\, t \in T
\end{aligned}
$$

Strategic Crew Balance: For all vehicles, crew stage bases, and time periods; the number of crews available tomorrow = number of crews available today + crews coming out of crew rest from previous direct, transshipment, and backchannel missions − crews required for departing direct, transshipment, and backchannel missions + the net crews made available from tanker deployments and returns (if APOE and tanker aircraft) + the net crews made available from

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"chopped" and "unchopped" vehicles (if "super" POD) + new crew allocations + arriving deadhead crews from other bases – deadhead crews departing for other bases.

MOG: base capacity

$$\sum_{i \in I} \sum_{a \in A} \sum_{r \in RD_b \cap RD_{ia,dir}} gtime_{abr} \cdot acpkg_{ab} \cdot \left[XD_{i,a,r,t-etrv_{abr}} + XDR_{i,a,r,t-etrv_{abr}} \right]$$

$$+ \sum_{i \in I_{b,dst}} \sum_{a \in A} \sum_{r \in RD_{ia,dir}} gtime_{abr} \cdot acpkg_{ab} \cdot XD_{i,a,r,t-trv_{ar}}$$

$$+ \sum_{i \in I_{b,dst}} \sum_{a \in A} \sum_{r \in RD_{ia,dir}} qtime_{abr} \cdot acpkg_{ab} \cdot XDR_{i,a,r,t-trv_{ar}}$$

$$+ \sum_{i \in I} \sum_{a \in A} \sum_{r \in RD_b \cap RD_{ia,trn}} gtime_{abr} \cdot acpkg_{ab} \cdot \left[XT_{i,a,r,t-etrv_{abr}} + XTR_{i,a,r,t-etrv_{abr}} \right]$$

$$+ \sum_{i \in I_{b,trn}} \sum_{a \in A} \sum_{r \in RD_{ia,trn}} gtime_{abr} \cdot acpkg_{ab} \cdot XT_{i,a,r,t-trv_{ar}}$$

$$+ \sum_{i \in I_{b,trn}} \sum_{a \in A} \sum_{r \in RD_{ia,trn}} qtime_{abr} \cdot acpkg_{ab} \cdot XTR_{i,a,r,t-trv_{ar}}$$

$$+ \sum_{i \in (I_{b,dst} \cap I_{fob}) \cup I_{b,trn}} \sum_{a \in A} sgtime_{ab} \cdot acpkg_{ab} \cdot XS_{iat}$$

$$+ \sum_{b' \in B_{sup} \cap BS_{b,dwn}} \sum_{a \in A} hrsper \cdot acpkg_{ab} \cdot \left[THCHOP_{ab't} + THCHOPR_{ab't} \right]$$

$$+ \sum_{a \in A} \sum_{r \in RB_{ab}} gtime_{abr} \cdot acpkg_{ab} \cdot Y_{a,r,t-etrv_{abr}}$$

$$+ I(b \in B_{tkr}) \cdot \left[\sum_{a \in A_{tkr}} hrsper \cdot acpkg_{ab} \cdot TKRB_{abt} \right]$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_{b,div} \cap RD_{ia,dir}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot XD_{i,a,r,t-etrv_{abr}}$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_{b,div} \cap RD_{ia,dir}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot XDR_{i,a,r,t-etrv_{abr}}$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_{b,div} \cap RD_{ia,trn}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot XT_{i,a,r,t-etrv_{abr}}$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_{b,div} \cap RD_{ia,trn}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot XTR_{i,a,r,t-etrv_{abr}}$$

$$+ \sum_{a \in A_{rfl}} \sum_{r \in RB_{b,div}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot Y_{art-etrv_{abr}}$$

$$\leq mog_b \cdot mogeff_b \qquad \qquad \forall \ b \in B \ except \ B_{sup}, B_{arp}, B_{way}, \ t \in T$$

Maximum On Ground: For all bases (except super pods, AR points, and waypoints) and time periods; the vehicle parking (refers also to berthing) required for transiting or terminating direct delivery missions + parking for transiting and terminating transshipment missions + shuttle mission parking (if FOB or transshipment POD) + chopped vehicle beddown parking (if shuttle

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beddown base) + divert base parking for failed refuelings of direct delivery, transshipment, and backchannel missions + tanker aircraft parking (if tanker aircraft and tanker beddown base) ≤ available MOG * MOG efficiency.

G.   VERIFICATION AND VALIDATION

We did initial validation of NRMOAS using NRMO as the baseline. We constructed a small scenario and ran it through both NRMO and NRMOAS. The results were exactly the same, so changes made to NRMOAS have not changed the basic functioning of the NRMO model. Additionally, we found no mathematical results in the solution file that would indicate NRMOAS was behaving in any unrealistic fashion. Ships are allocated only to ports and travel only on sea routes, taking the appropriate amount of time to transit and carrying the right amount of cargo. We recommend further more stringent validation against other models currently in use. In particular, we recommend a comparison with MIDAS as follow on research.

IV. SCENARIOS

We ran three similar scenarios through NRMOAS and FDE. Each scenario and the results obtained are described in this chapter. Additionally, we ran one scenario through NRMOAS both in the user-designating mode and the model-designating mode. These results are also compared.

A. ASSUMPTIONS AND INFORMATION COMMON TO ALL SCENARIOS

1. All units can be assumed to make their ALD.

2. All passengers are moved by aircraft only.

3. For NRMOAS runs, all bases were given an unlimited supply of fuel. FDE does not consider the amount of fuel available on bases as a separate constraint. Also, data on fuel availability was generally poor in that most airfields and ports are considered to have unlimited fuel capacity.

4. NRMOAS assigns lift assets to units in order to minimize the weighted sum of late and undelivered cargo penalties (Baker, 1997, p. 55). It does not actually prioritize units except in the sense that it will assign assets to move a unit with an earlier RDD before a unit with a lower RDD. FDE prioritizes units as a function of tonnage and the inverse of the square of the unit priority time the RDD (FDE URM 1998, p. 3-1):

$$unit\ priority = f\{tonnage, 1 / (priority * RDD)^2\}$$

The actual function is not given in the URM and was not available from the contractor, so we assumed that setting all unit priorities in FDE to one would allow both models to prioritize in the most similar manner.

5. Initial NRMOAS runs were done on a PC with a Pentium Pro processor, a 3.1 GB hard drive and 32 MB of RAM. Additional runs were done on an IBM RS6000 workstation with 1 GB of RAM, and a second PC with a Pentium II Processor and 500 MB of RAM.

6. All FDE runs were done on a Sun SPARC Work Station with, 224 MB of physical memory and 425 MB of virtual memory.

7. All FDE runs used the following parameters:

   a. FDE was only run in simple mode. This is a deterministic mode where input values such as speed were fixed at their expected value. No variable inputs were used.

   b. Minimizing lateness for units was the only model goal selected.

   c. FDE was told to stop if it reached twenty consecutive infeasible solutions.

8. The scenarios run through NRMOAS and FDE were originally designed as duplicates. Nevertheless, some network differences occurred due to the data input requirements of each program, (described in Chapter IV, Section C). Additionally, we noted some discrepancies in unit load requirements in the data sets created by other sources. These discrepancies occurred when the FDE data files were built separately by a SETA analyst and sent to the Naval Postgraduate School for use (see Chapter IV, Section C). We documented the differences for each scenario.

9. Unit closure is defined as receipt of 100% of all cargo and personnel.

B. RESULTS

1. Scenario # 1

We designed this scenario to give a baseline for comparison. Movement assets are sufficient to meet all RDD's. It consists of twenty-four units including nine Air Force flying squadrons, one Army armored division, one Army mechanized division, one Army air assualt division, various Army combat service support units and one USMC regimental landing team. Total cargo requirements are shown below in short tons:

Bulk Cargo: 210293

Oversized Cargo: 162500

Outsized Cargo   115250

Pax: 156483

Lift assets for this scenario are plentiful. The aircraft and ships available are based on J8/WAD's estimates for the total assets that the United States could mobilize in the event of a Major Theater War. The assets, as well as their availability dates, are shown below in Table 1.

Day	Asset	Is	Available								
Asset	1	3	7	12	15	16	20	21	25	45	65
C5	56	10	12	15							
C17	80			11							
KC10	32			4							
KC135	7										
NBC			3	12			24				
WBC				22			32				
WBP				15			54				
BB						10		12			40
FSL					8						
LASH						4				8	
LMSR					11					10	
RORO					36				8		10

Table 1. This table shows the maximum number of assets that would be available for use during an MTW. It includes both military and CRAF air assets, as well as merchant marine shipping. Naval and MPS shipping is not considered. Day 1 is the first movement day. NBC, WBC and WBP refer to three types of civilian aircraft in the Civil Reserve Aircraft Fleet (CRAF). They are, respectively; Narrow Body Cargo, Wide Body Cargo, and Wide Body Pax. Ship types are defined in Chapter Three, Section D.

Delivery windows ranged from a minimum of 15 days to a maximum of 45 days. Differences from NRMOAS to FDE are; NRMOAS used thirteen source nodes while FDE used only six and based on differences in data input, FDE was required to move approximately 10% less cargo.

NRMOAS showed no real deviation from the delivery requirements (see Figures 3 and 4). 99.8% of cargo was delivered on time, as were 100% of personnel. 95.8% of units attained cargo closure and 100% attained personnel closure by their RDD (see Figures 7 and 8).

FDE was unable to meet delivery requirements, needing 16 days beyond the latest RDD to deliver all cargo (see Figures 5 and 6). Only 70.1% of units attained closure with cargo by their RDD and up to 18 days were required for the last unit to receive all its cargo. Personnel deliveries showed similar results, with only 83.3% of units attaining personnel closure by RDD. Five days was required for the last unit to receive all its personnel (see Figures 8 and 9).

Percent Cargo Delivered – Actual vs. Required (NRMOAS Scenario 1)

Percent Pax Delivered – Actual vs. Required (NRMOAS Scenario 1)
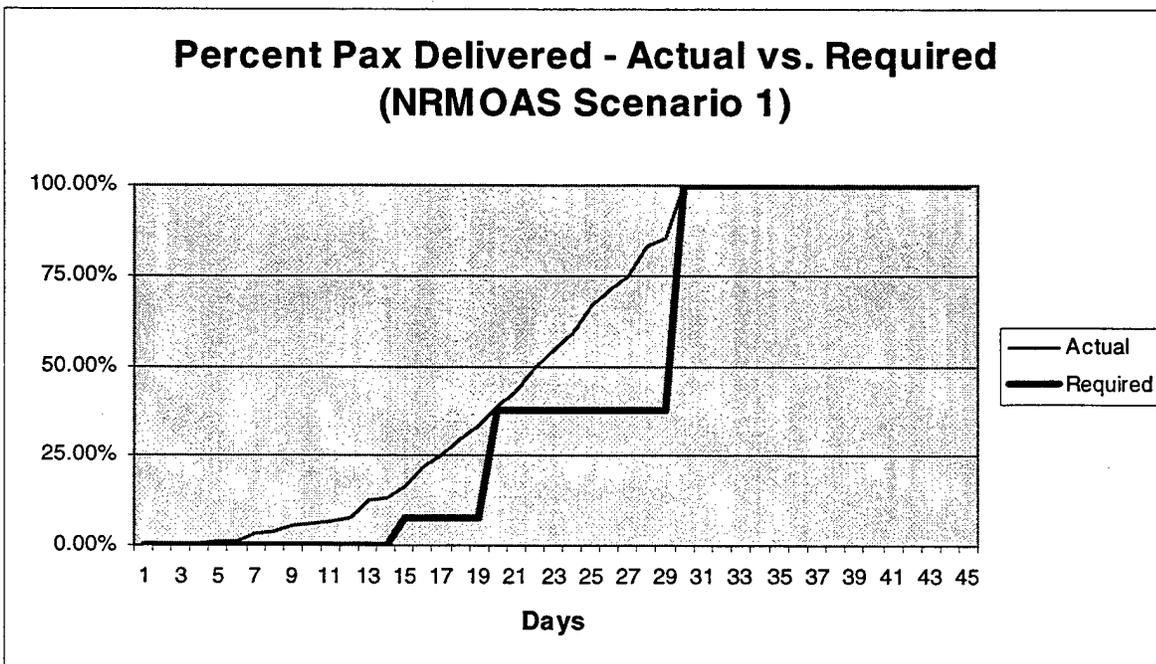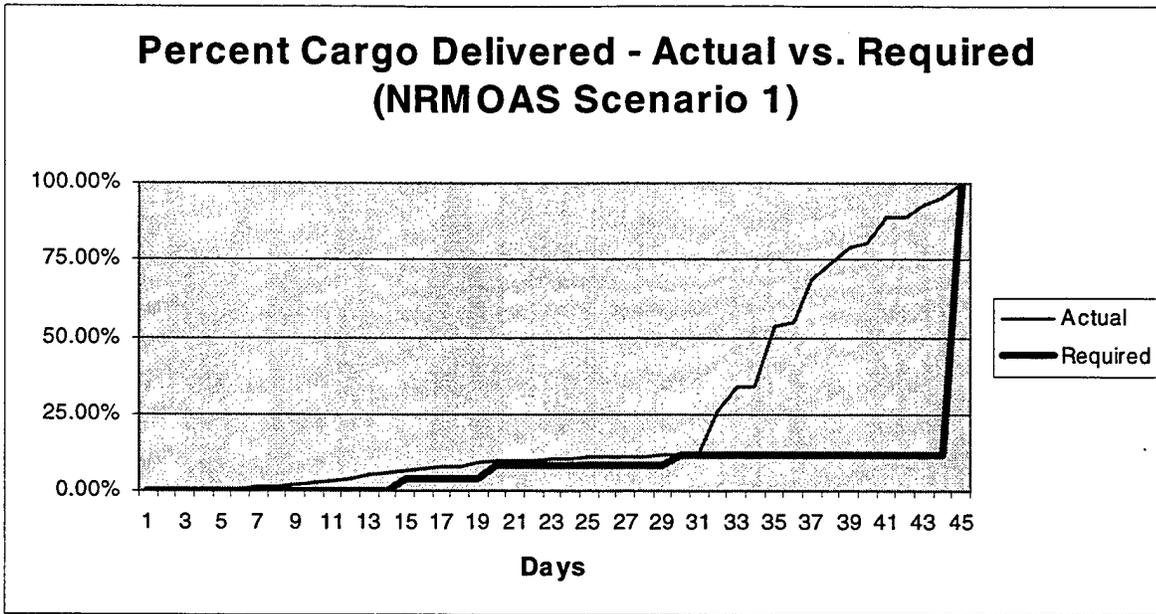
Figures 3 and 4. These graphs show the actual deliveries plotted against the requirements for both cargo and personnel. The heavy line represents requirements, while the thin line shows the actual deliveries. All cargo was delivered within 45 days and all personnel were delivered within 30 days. The large spikes on the required deliveries line are due to scenario design. They do not represent an actual TPFDD, but rather a simplified replication developed strictly for comparison of the two models.

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Percent Cargo Delivered - Actual vs. Required (FDE Scenario 1)

**Percent Pax Delivered - Actual vs. Required (FDE Scenario 1)**
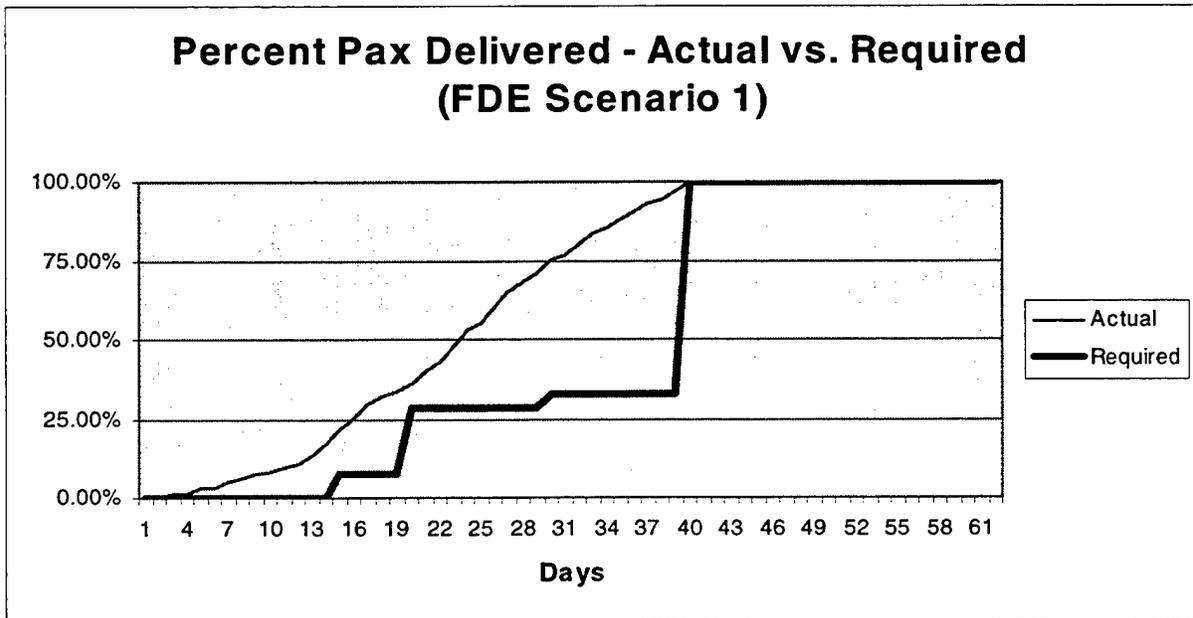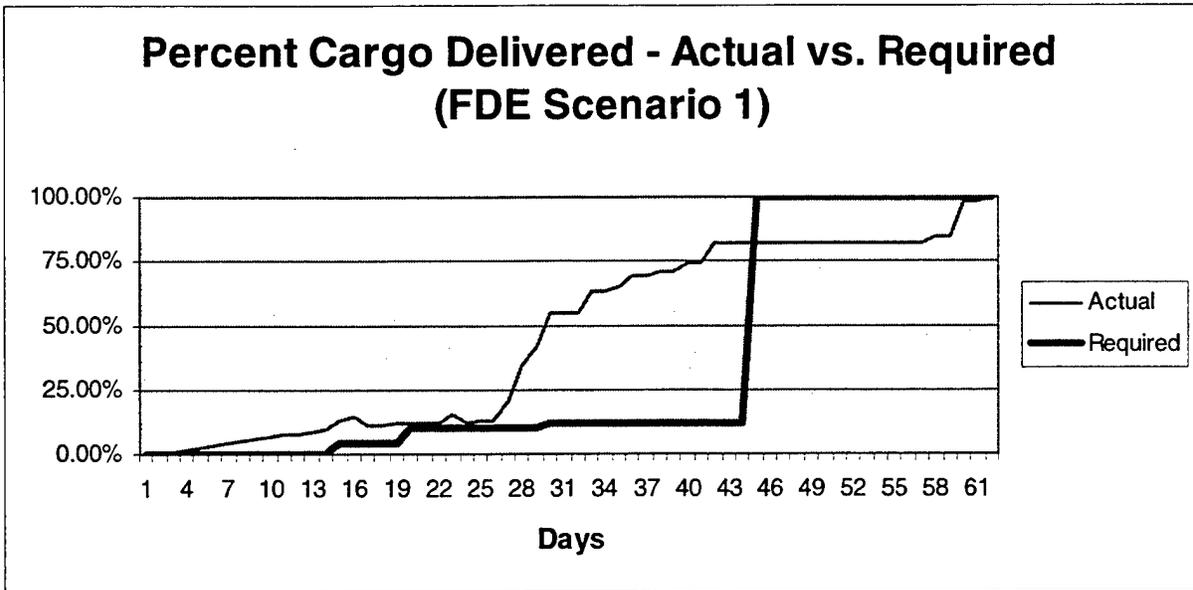
Figures 5 and 6. FDE was able to deliver all personnel before the final RDD, but needed 16 additional days to deliver all cargo. Cargo delivery reached approximately 80% of requirements by the last RDD of 45 days.

**Unit Closure - Cargo
(FDE vs. NRMOAS - Scenario 1)**
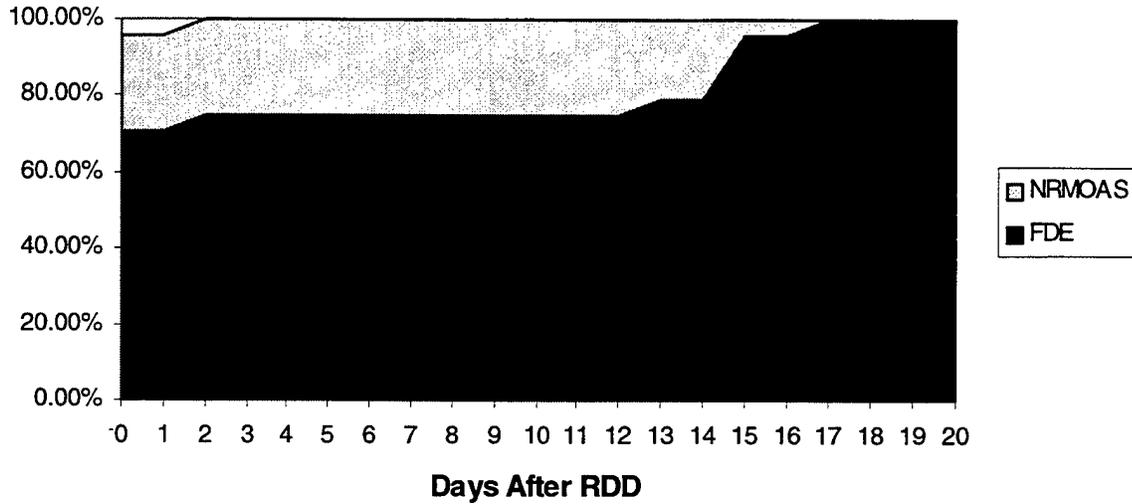
**Unit Closure - Pax
(FDE vs. NRMOAS - Scenario 1)**
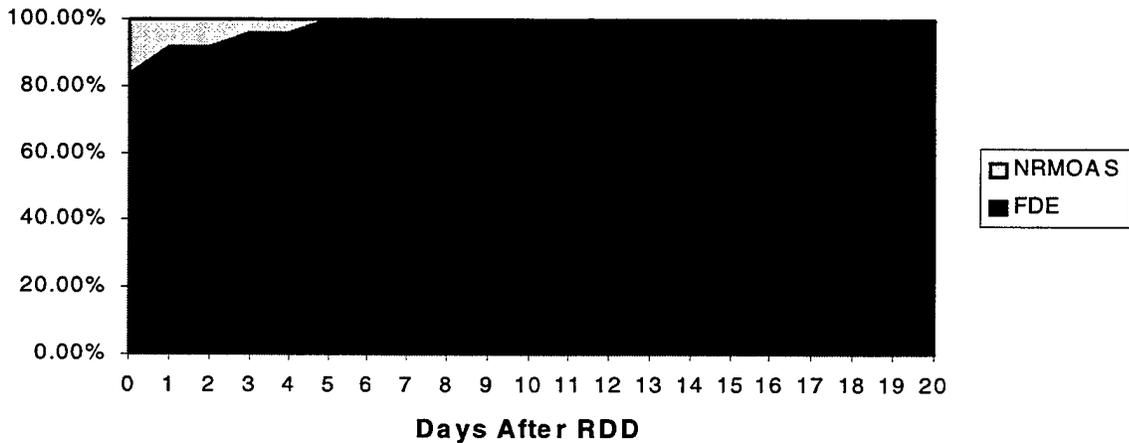
Figures 7 and 8. These graphs display the unit closure rates in terms of days after RDD. NRMOAS achieved on-time personnel closure for 100% of units and cargo closure for 95.8%. In the one case that NRMOAS did not close by RDD, 2 days were required for the unit to close. FDE achieved on-time personnel closure for 83.1% of units and on-time cargo closure for 70.1%.

2. Scenario # 2

We designed this scenario to test the abilities of both programs in terms of achievement of delivery windows. Units used and delivery windows are the same as Scenario 1, however there was a significant reduction in assets. Assets for this scenario are shown in Table 2:

Asset	Day Asset Is Available											Asset Reduction
	1	3	7	12	15	16	20	21	25	45	65	
C5	18	3	4	5								63
C17	26			4								61
KC10	10			2								24
KC135	2											5
NBC			1	4			8					26
WBC	-			7			11					36
WBP				7			26					36
BB						5		6			19	33
FSL					3							5
LASH						1				3		8
LMSR					3					7		11
RORO					12				3		3	36

Table 2. This table shows the number of assets used for Scenario #2. The number of assets eliminated from Scenario 1 is shown in the right column.

The reduction in assets had a significant affect on NRMOAS's ability to make deliveries on time. NRMOAS required an additional 30 days beyond the last RDD to complete delivery of cargo, while an additional 17 days was required for personnel (see Figures 9 and 10). Unit closure was also affected, with the number of units attaining cargo closure by RDD dropping to 29.9% and the number attaining on-time personnel closure dropping to 25% (See figures 13 and 14).

FDE was affected by the reduction in assets to a far greater degree than NRMOAS. FDE required 40 additional days beyond the last RDD to complete delivery of cargo and 11 additional days for personnel (see Figures 11 and 12). On-time delivery rates also dropped

severely, with just 12.5% of units receiving all their cargo and 20% receiving all their personnel by their RDD (see Figures 13 and 14).

Percent of Cargo Delivered - Actual vs. Required (NRMOAS Scenario 2)

**Percent Pax Delivery - Actual vs. Required (NRMOAS Scenario 2)**
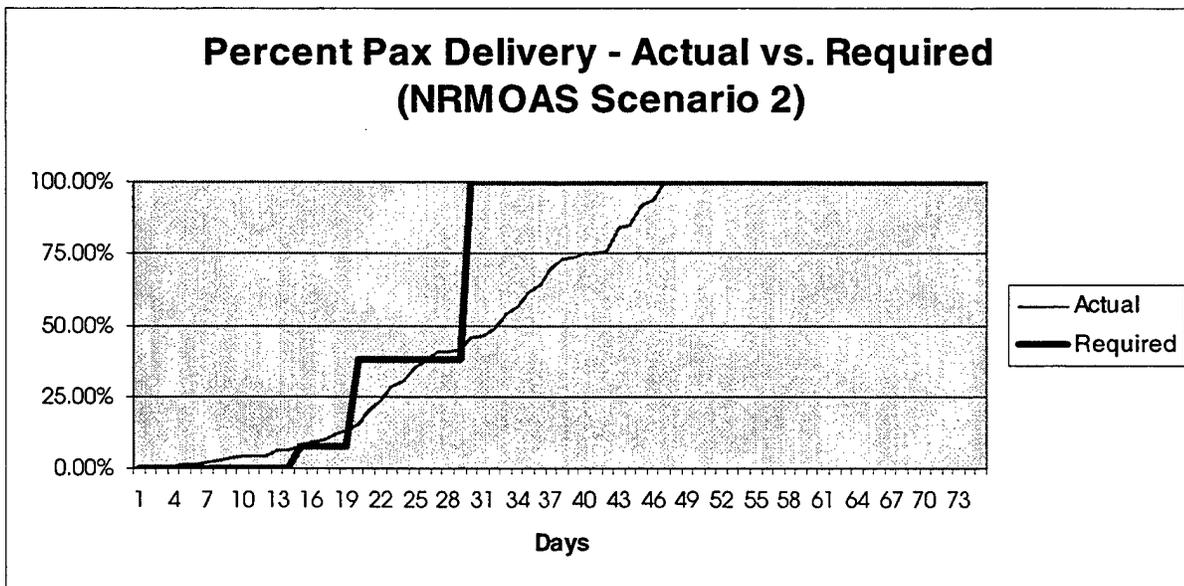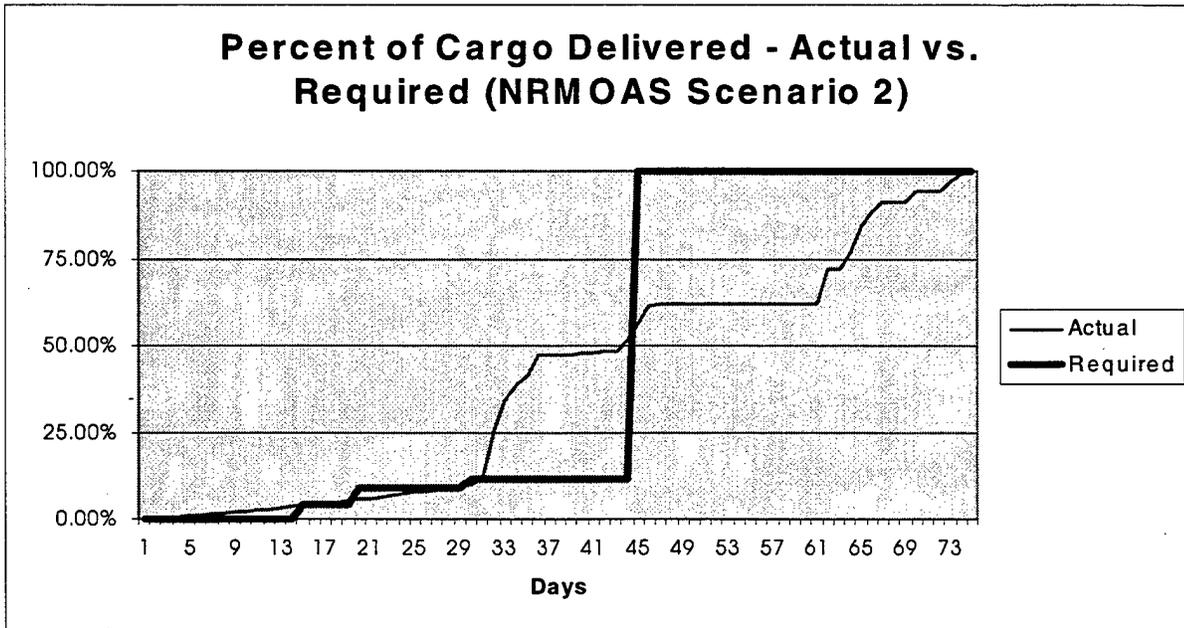
Figures 9 and 10. The affects of a 2/3 reduction in lift assets from Scenario 1is shown here. Actual deliveries were able to stay ahead of required deliveries for cargo up to day 45, the last RDD. Although the flow of cargo and personnel remained constant, the slope of the actual delivery line indicates a much slower buildup than Scenario 1.

Percent Cargo Delivered - Actual vs. Required (FDE Scenario 2)

**Percent Cargo Delivered - Actual vs. Required (FDE Scenario 2)**
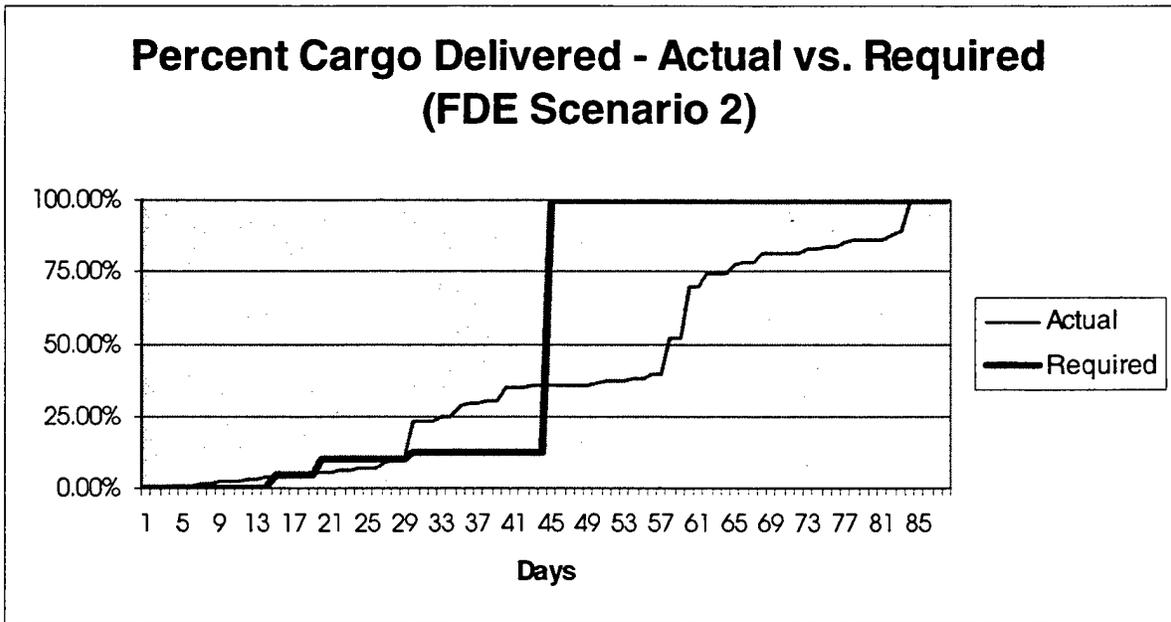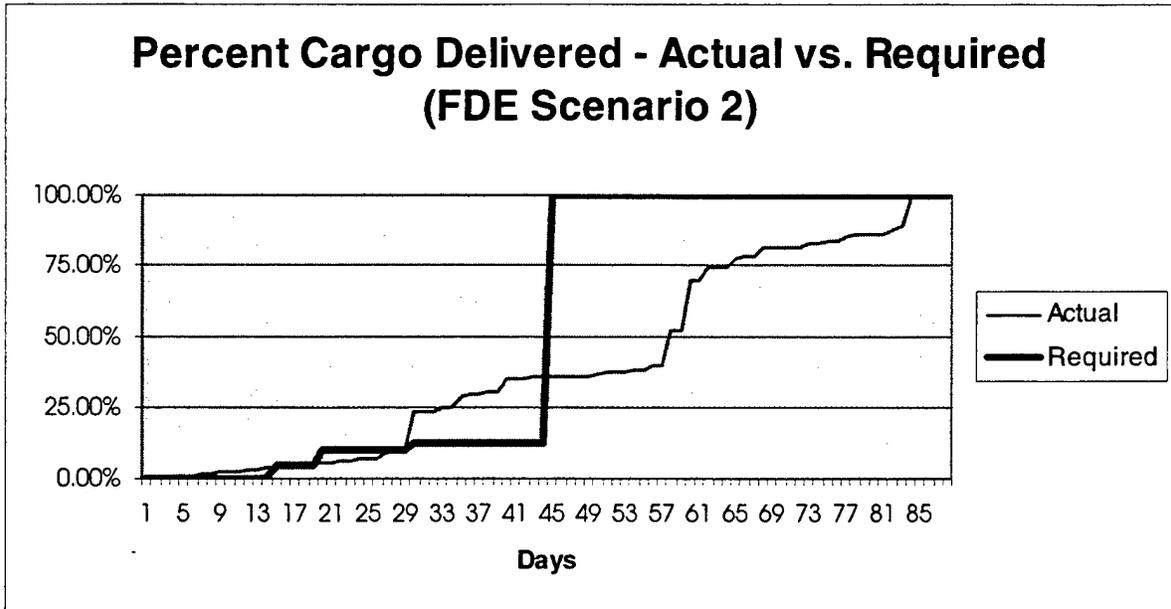
Figures 11 and 12. The reduction in assets greatly affects FDE's ability to deliver cargo on time. With less than 50% of the cargo required delivered by day 45, FDE required 85 days to move all units into theater. Personnel deliveries showed a similar trend, with less than 75% of personnel arriving by day 45.

Unit Closure - Cargo
(FDE vs. NRMOAS - Scenario 2)
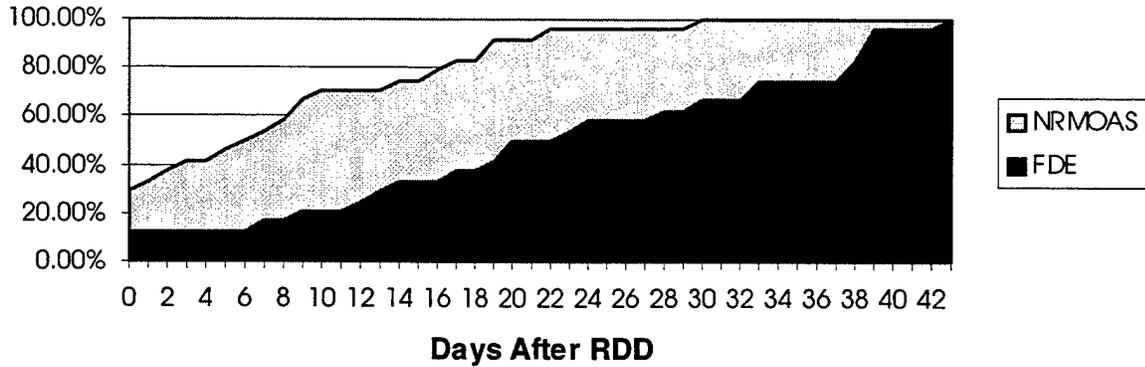
Unit Closure - Pax
(FDE vs. NRMOAS - Scenario 2)
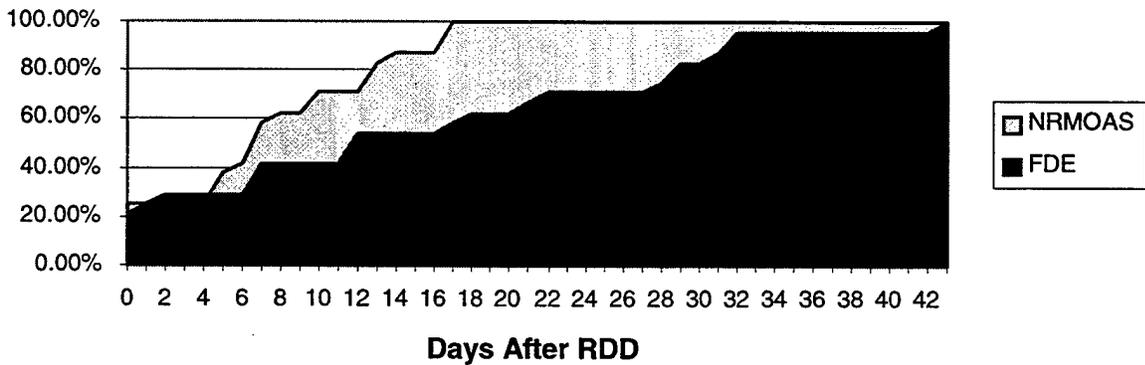
Figures 13 and 14. Asset reduction severely impacted on-time deliveries of both models but much more so for FDE. NRMOAS dropped the number of units that received all their cargo by RDD to 29.2% and the number that received all personnel by RDD to 25%. The last unit required 30 days to attain cargo closure. FDE showed an even more significant reduction in cargo closure, dropping to 12.5%. FDE personnel closure dropped to 20.83%

3. Scenario # 3

We designed this scenario to test each program using a larger contingency. It consists of sixty-one units, and includes one Army armored division, one Army mechanized division, three Army mechanized brigades, two Army armored cavalry brigades, one Army armor brigade, three Army light infantry brigades, two Ranger regiments, two Special Forces Groups, various Army combat support and combat service support units, two USMC regimental landing teams, a Maritime Prepositioning Fly-In-Echelon, and twenty-eight Air Force flying squadrons. Total cargo requirements are shown below in short tons:

Bulk Cargo: 417473

Over Sized Cargo: 277018

Out Sized Cargo   1733972

Pax: 315575

Assets for this scenario are the same as those in Scenario #1 (see Table #1). Delivery windows ranged from a minimum of 15 days to a maximum of 45 days. As with Scenarios 1 and 2, we noted several differences between NRMOAS and FDE's data. In this case, NRMOAS used fifteen source nodes while FDE used only six, and again, based on differences in data input, FDE was required to move approximately 14% less cargo and 5% more personnel.

NRMOAS was able to deliver 100% of personnel, but only 94.2% of the cargo (Figures 15 and 16). The 5.8% nondelivery of cargo is caused by a NRMOAS parameter called "maxlate". "Maxlate" is a user defined parameter that is the maximum number of days after a unit's RDD that cargo and personnel can be delivered. If cargo cannot be delivered by this day, it is not delivered at all. "Maxlate" was set to 30 days for this scenario. In this case, the unit affected was moved by air, had an RDD of 45 days and received only 52.2% of its cargo.

The additional heavy requirements decreased the number of units attaining cargo closure by RDD to 72.1% and the number attaining personnel closure by RDD to 67.2% (see Figures 19 and 20).

Although the model parameters were set for 26 trial solutions, FDE repeatedly crashed after obtaining only one feasible solution, which is reported here. FDE delivered all required cargo and personnel within 65 days. Had a 30 day cut-off restriction similar to NRMOAS's "maxlate" been applied to FDE, cargo deliveries would still have exceeded 99%, while personnel would have dropped to 96.8% (see Figure 17 and 18). 96.7% of units achieved cargo closure of 30 days, while 80.3% of units attained personnel closure within the same period. Of concern, however, are the on-time delivery statistics. Only 48.9% of units cargo closed by their RDDs, while only 32% of the personnel closed by their RDD.

Percent Cargo Delivery - Actual vs. Required (NRMOAS Scenario 3)

Percent Pax Delivery - Actual vs. Required (NRMOAS Scenario 3)
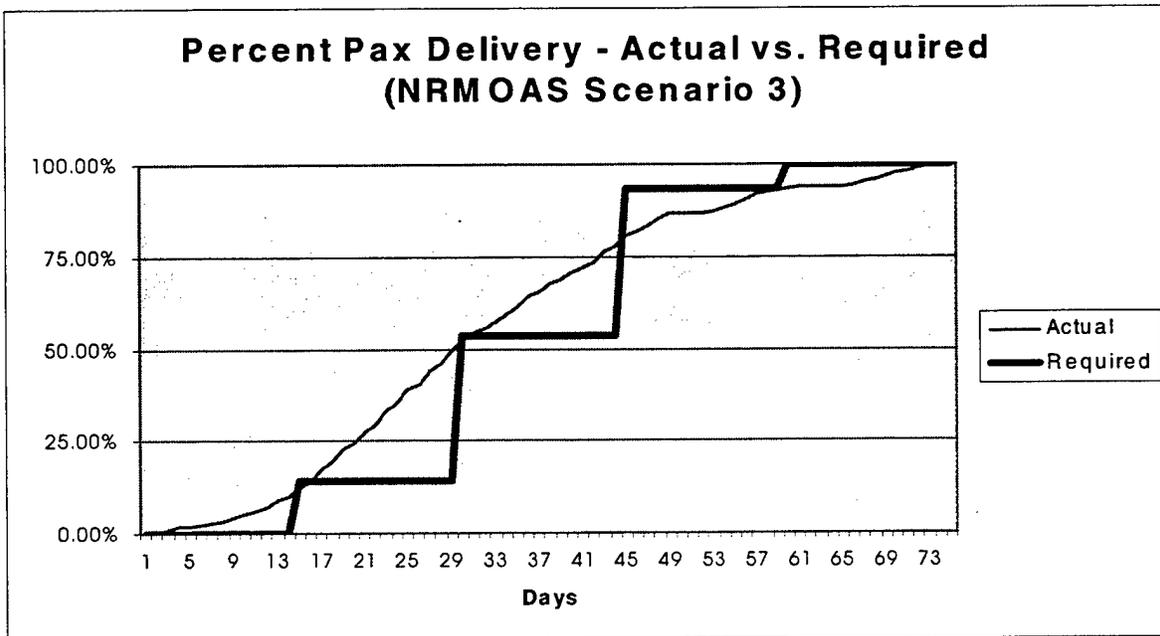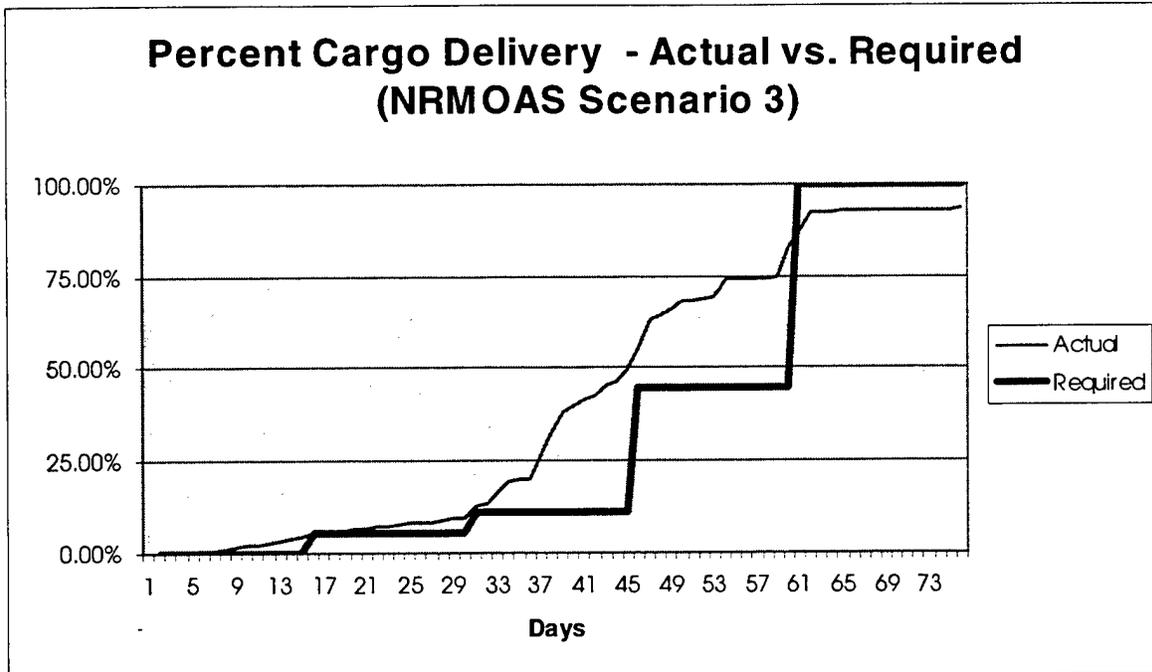
Figures 15 and 16. Increasing the amount of cargo and personnel to be moved did not greatly affect the overall delivery profile. NRMOAS still remained generally ahead of its requirements throughout most of the deployment. 100% of personnel were delivered, but only 94.2% of cargo. Similar to the delivery requirements in Scenario 1 and 2, the large spikes on the required delivery line are a reflection of the simplified TPFDD used in this scenario.

**Percent Cargo Delivered - Actual vs. Required
(FDE Scenario 3)**
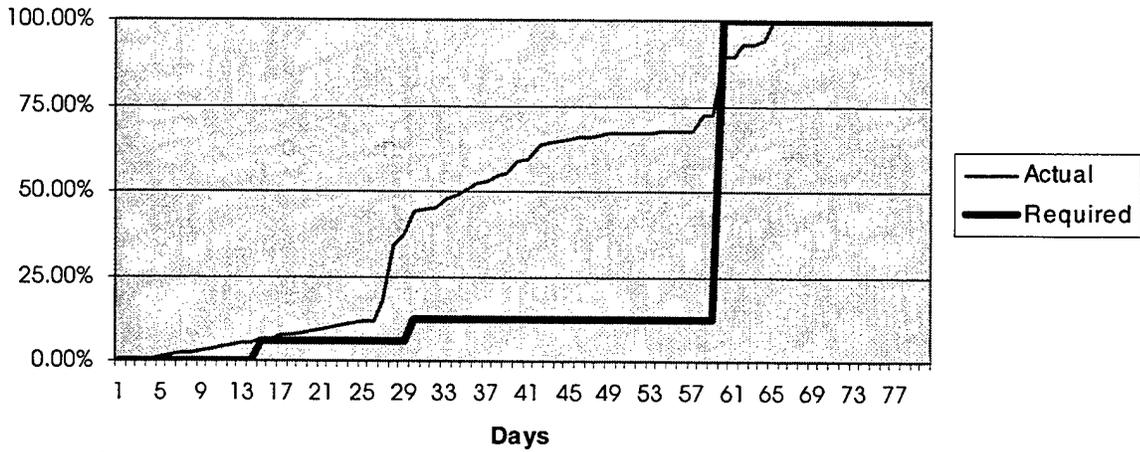
**Percent Pax Delivered - Actual vs. Required
(FDE Scenario 3)**
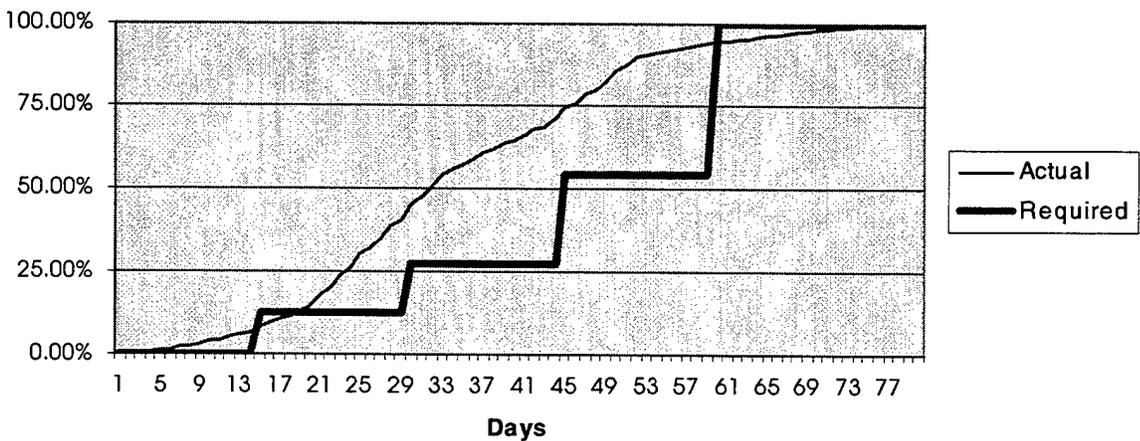
Figures 17 and 18. FDE was able to deliver all cargo and personnel to the theater of operations. Even the addition of the 30 day cut-off requirement found in NRMOAS would have reduced the delivery of cargo by only 0.1% and the delivery of personnel by less than 2%.

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**Unit Closure - Cargo
(FDE vs. NRMOAS - Scenario 3)**

**Unit Closure - Pax
(FDE vs. NRMOAS - Scenario 3)**
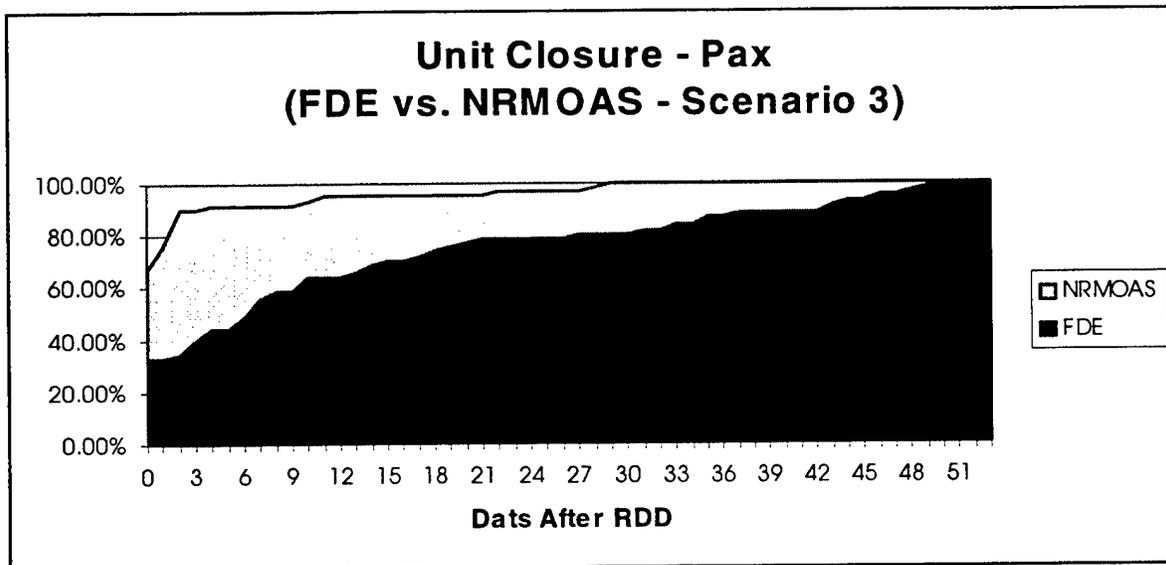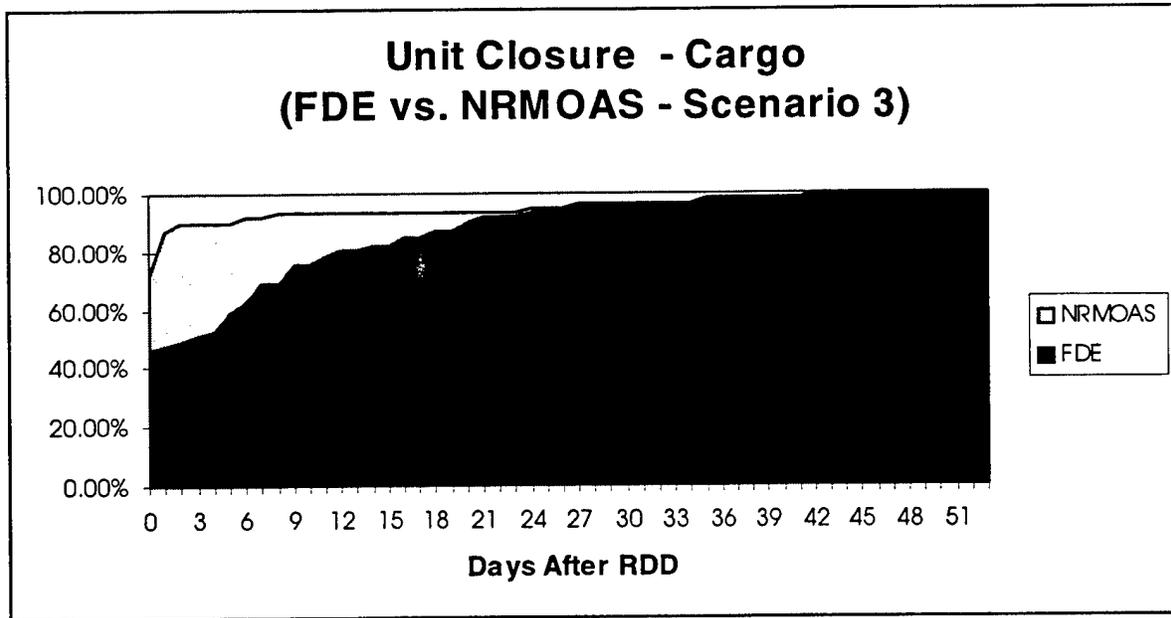
Figures 19 and 20. The large amount of cargo and personnel to be moved in Scenario 3 caused NRMOAS to drop the number of units achieving closure by RDD to 72.1% for cargo and 67.2% for personnel. In both cases, 90% of the units closed within 2 days of their RDD's, leaving just three units needing to receive deliveries of cargo or personnel. All personnel were delivered within 30 days; however, one unit never received its full requirement of cargo because it could not be delivered within 30 days of that unit's RDD. FDE's unit closure rate also dropped; to 45.9% for cargo and 37.8% for personnel. Additionally, the final unit to close with cargo received its last shipment 42 days past its RDD. Similarly, the final unit to close with personnel received it last delivery 32 days after its RDD. IN all scenarios NRMOAS produced more favorable closure profiles than FDE.

4.   NRMOAS Mode Selection Comparison

As discussed in Chapter III, NRMOAS can be run in two different modes: User Select Mode, where the user designates which mode of travel each unit uses, and Model Select Mode, where the model designates which mode of travel the unit uses. In addition to the comparsion with FDE, we ran Scenario #3 in the NRMOA model select mode. The only difference in the scenarios was a slight deviation in RDDs for personnel. Personnel are moved only by air; therefore, when using the user select mode, it is necessary to divide those units whose cargo moves by sea into two line id's, one for personnel and one for cargo. In doing this, we gave the personnel an earlier RDD. When using the model select mode, it is not necessary to split the units, so both cargo and personnel were given the same date.

The most important result from the two runs is that in the model select mode, NRMOAS delivered 100% of cargo amd personnel to the theater of operations, an improvement over the 94.3% delivery of cargo in the user select mode. Additionally, while on-time delivery rates did not improve greatly, closure rates for both cargo and personnel did. (see Figures 21 and 22).

Unit Closure - Cargo
NRMOAS Model vs. User Mode Selection

Unit Closure - Pax
NRMOAS Model vs. User Mode Selection
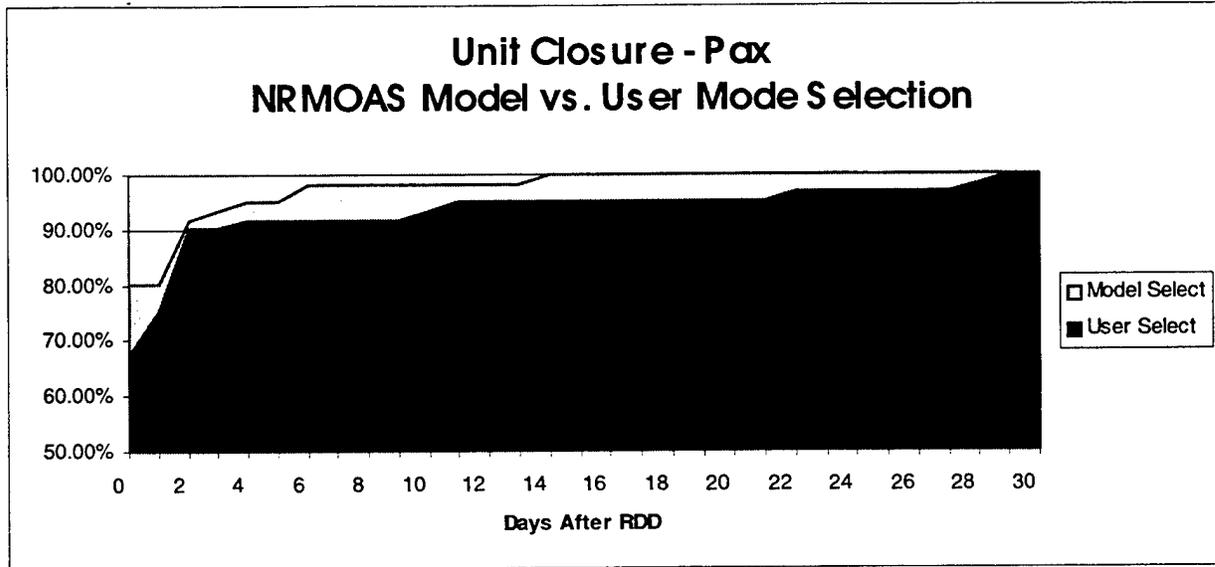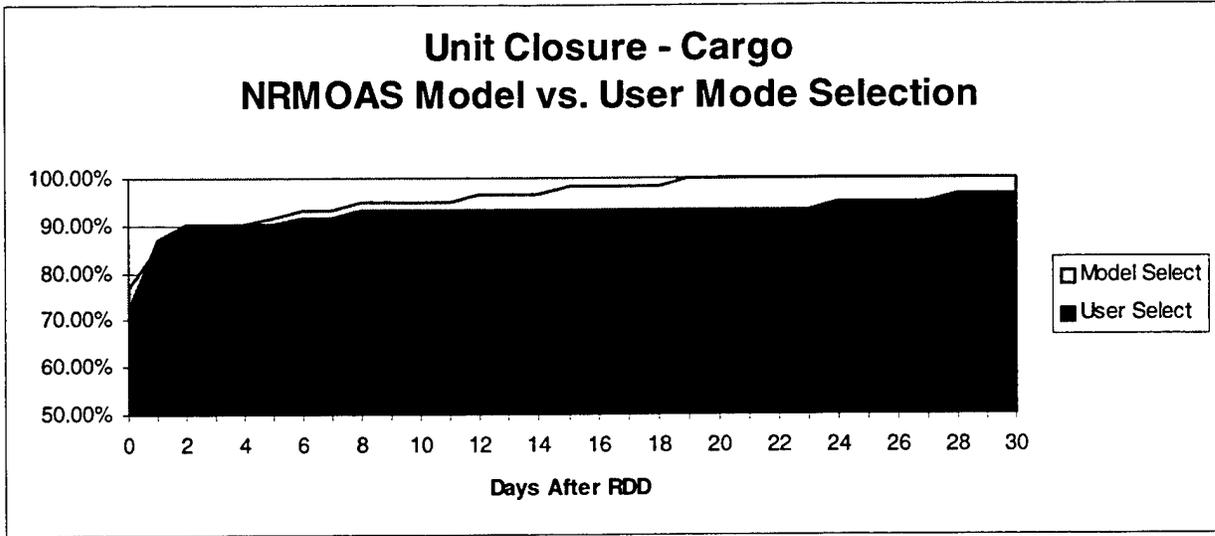
Figures 21 and 22. In the model selection mode on-time deliveries for cargo increased from 72% to 77%. The most noticeable change however, was that all units closed within 19 days. On-time delivery of personnel showed a much greater increase, from 67% to 80%. Additionally, all personnel closed by day 14, a 14 day decrease from NRMOAS in the user select mode. (Note that the graph scales start at 50%.)

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Figures 23 and 24 show the differences in how cargo was moved. The only major difference is in bulk cargo. When NRMOAS selected the mode of movement, significantly more bulk cargo was moved by air than by sea.

Cargo Deliveries By Air

Cargo Deliveries By Ship
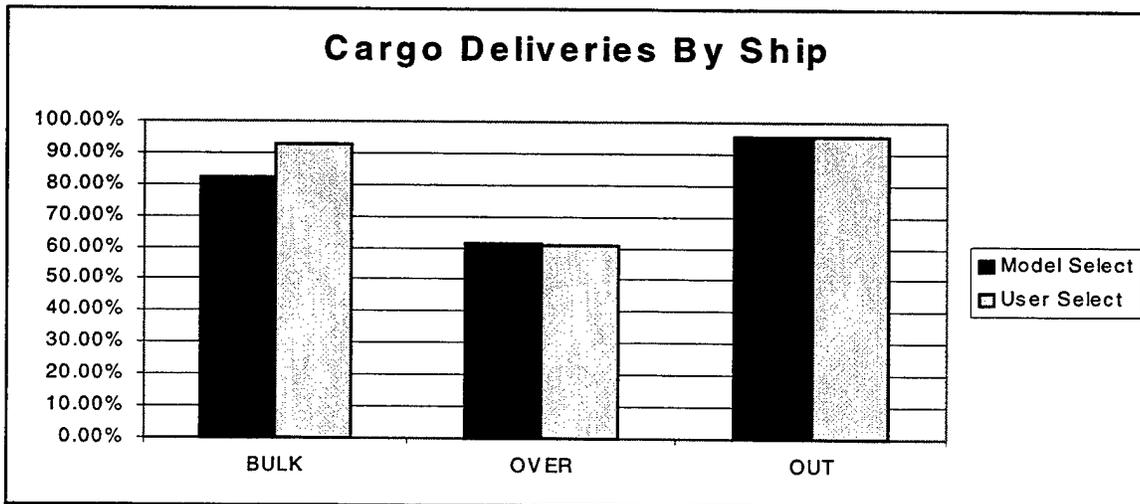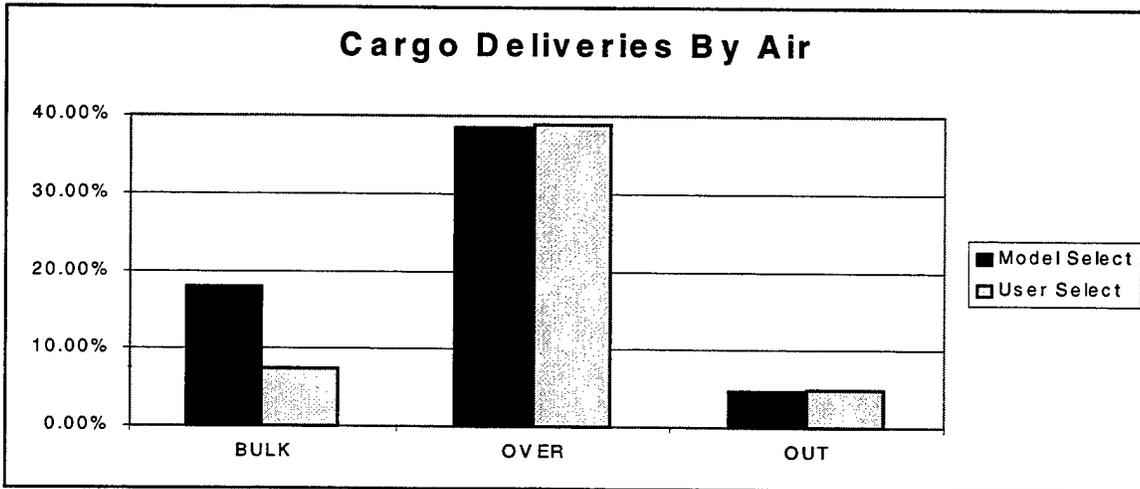
Figures 23 and 24. These figures show the amount of cargo delivered by air and sea under full optimization (Model Select mode) and partial optimization (User Select mode). Amounts of cargo delivered did not change greatly, with exception of bulk cargo. NRMOAS in model select mode found airlift a more effective way to move bulk cargo. Percentages are calculated as the percentage of cargo delivered , vice required. This is to account for the undelivered cargo from Scenario 3.

We also discovered a difference in the usage of the C17, WBC and WBP aircraft. In the user select mode, unit personnel and cargo were moved as separate line id's with different

RDD's, normally earlier for the personnel than for the cargo. Because more personnel were required to arrive in theater than the use of CRAF assets would allow, the C17 was used to move a large amount of personnel instead of cargo. While this is not the preferred use of a C17, the model responded in the way it should have, using the best assets available to achieve its RDD's. When used in model select mode, unit personnel and cargo had the same RDD's, which allowed a later arrival time for personnel than from the user select mode scenario. Again, the model responded as it should, using the C17 to carry cargo and saving the personnel for the WBP. Thus, the C17 was used less frequently, but more efficiently in the model select mode. The WBC aircraft was also used more frequently by the model select mode, carrying bulk cargo that was initially moved by sea.

C. OVERALL COMPARISONS

1. Data Preparation

Data preparation in NRMOAS requires some knowledge of GAMS and its requirements for file formatting. GAMS files are written as text files, so once the user is comfortable with these aspects of preparation, the process is fairly straightforward. Of the five data input files, calc.inc requires no alteration from scenario to scenario. The calculations it makes remain the same regardless of scenario specfics. Scenario.inc contains some scenario information such as aerial refueling points, tanker beddown points and crew staging bases; however, we did not use these factors in the scenarios, so that file also remained unchanged. Acdat.inc contains asset specific information and requires an update when the type or availability of assets changes. Routes.inc contains network data and therefore must be updated with every new scenario. Gamsagg.set also differs for every scenario as it contains all unit data, to include load and delivery time windows, and all base data including locations and

capabilities. NRMO can generate the unit and carrier load information portions of gamsagg.set using an Air Force TPFDD and the Air Flow Model (AFM), however the carrier capacity data generated in this fashion contains only aircraft data and is not useful to NRMOAS. Instead, TPFDD data, as well as aircraft and ship capacity data, must be input by hand.

For NRMOAS, resolution of TPFDD data can be done to whatever degree the user desires. For these scenarios, resolution was down to the squadron level for Air Force units, the brigade and division level for Army units and the regimental level for USMC units. Once a base file is created, changes can be made fairly rapidly to reflect new scenarios.

FDE data files are built and edited via the GUI. No preprocessor is available, so TPFDD data must be input manually. As with NRMOAS, the level of resolution of the TPFDD can be determined by the user; however, most existing FDE units are squadron-, brigade- or division-sized.

FDE GUI is slow and tedious. It requires most entries to be made one at a time and does not allow minor changes to be made easily. For example, to reduce the number of C5's available for use on a given day from 56 to 20, the user has two options: either delete 26 C5's one by one, confirming each deletion via a pop-up window; or delete all the C5's and add back in the 20 the user wants. A much simpler method would be to allow the user to highlight and delete more than one item at a time. Similar editing options through out all screens make creating or changing existing files very slow.

The most difficult part of building the FDE data file is setting up the network. One problem we encountered while building the networks is that paths from a source node to a sink node that contain more than four links cause FDE to crash. This severely limits the realistic geographical depiction of a deployment network. For example, it is impossible to portray a realistic sea route from a seaport in the Gulf of Mexico to the port of Ad Damman, on the east

coast of Saudi Arabia with only four links. Additionally, FDE had trouble finding solutions when the network was composed of multiple sources with small amounts of cargo. This requires that the network be built using a smaller number of aggregate embarkation bases. In the case of these comparison scenarios, NRMOAS used 12 or 13 source nodes, while FDE used 6.

In most cases, FDE files are built using the fort.1 legacy file, which contains extensive unit and carrier information. The fort.1 file serves as a shell from which desired scenarios are built. In the absence of the fort.1 file, building files can be extremely challenging. In fact, building files from scratch is highly discouraged by experienced FDE users. We encountered numerous problems during the course of this thesis while building FDE data sets from scratch. Eventually, we used data files that were built by a SETA Corporation analyst, using the fort.1 file. We encountered some discrepancies in the unit load requirements data, which accounted for the differences in cargo requirements between the NRMOAS and FDE runs.

2. Cargo Delivery

In all but one case, both models were eventually able to deliver all cargo and personnel to the theater of operations. The greatest difference between the models was in percentages of on-time deliveries. Here, NRMOAS was clearly superior. Overall, high and low on-time delivery rates are shown in Figure 25.

On-Time Deliveries
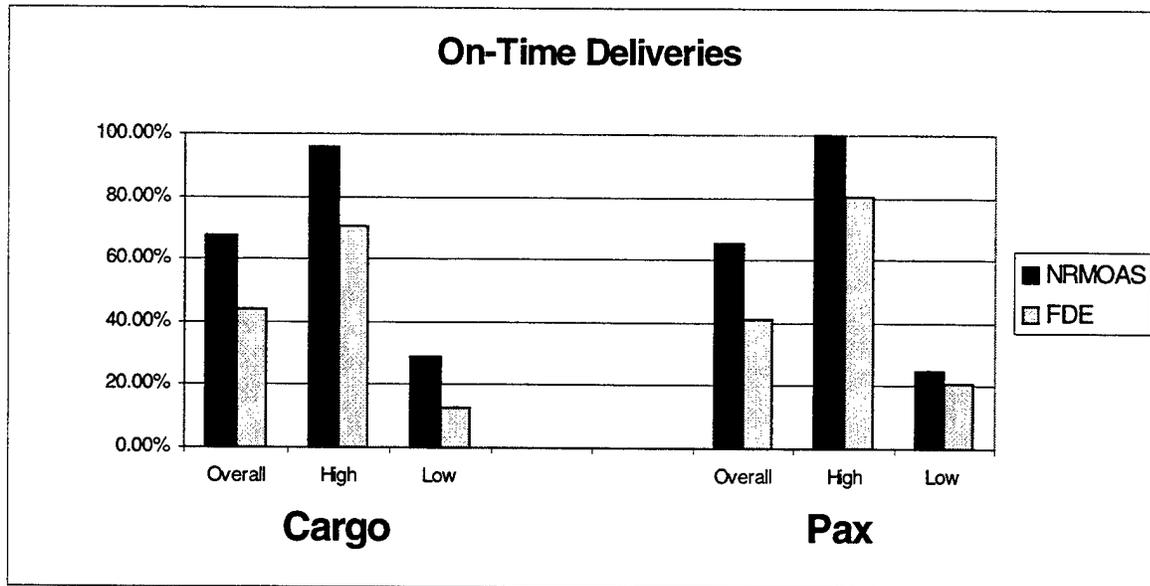
Figure 25 This graph is a compilation of NRMOAS's and FDE's delivery rates over all three scenarios. The overall column includes the total number of units delivered on-time over all three scenarios. High and low columns indicate the maximum and minimum on-time rates achieved.

While there are may be numerous factors that contribute to the differences in NRMOAS's and FDE's results, two of the major ones are first, asset utilization rates and second, initial allocation methods. Both NRMOAS and FDE require that each lift asset be given a utilization rate. This "ute rate", determines how many hours a day that a certain asset can be flown or sailed. Utilization rates used in all three scenarios are shown in Table 3.

Asset	C5	C17	KC10	KC135	NBC	WBC	WBP
Ute Rate	10.87	15.15	12.5	6	10	10	10

Table 3. Utilization rates determine the number of hours per day that an aircraft can be flown. Ship utilization rates have been omitted, because ships are not subject to crew rest or down time when traveling and therefore operate 24 hours a day. NRMOAS uses this data in hours per day, whereas FDE converts to fractions of a day.

NRMOAS sums the number of hours an aircraft is flown and balances it with that aircraft's utilization rate to determine if the aircraft can fly a subsequent mission. Flight times

are balanced over a user determined period of time, which we set to 5 days. This allows the model a certain amount of flexibility when assigning aircraft to missions.

FDE takes the same figure, as a fraction of 24 hours. It then multiples this number by the total amount of assets available and uses the remaining number of aircraft 24 hours a day. This information is not documented anywhere, but was explained by the SETA analyst who assited us by building data files. No explanation of how FDE handles ground time was given. Based on this reduction method, if there are 56 C5's available on day one, FDE will only use 26 of them to account for their utilization rate of 0.4529. FDE always rounds this number up so the user never ends up with 0 aircraft due to utilization rate. This method dramatically reduces FDE's available lift assets. Figure 26 shows the differences in aircraft available to NRMOAS and FDE.
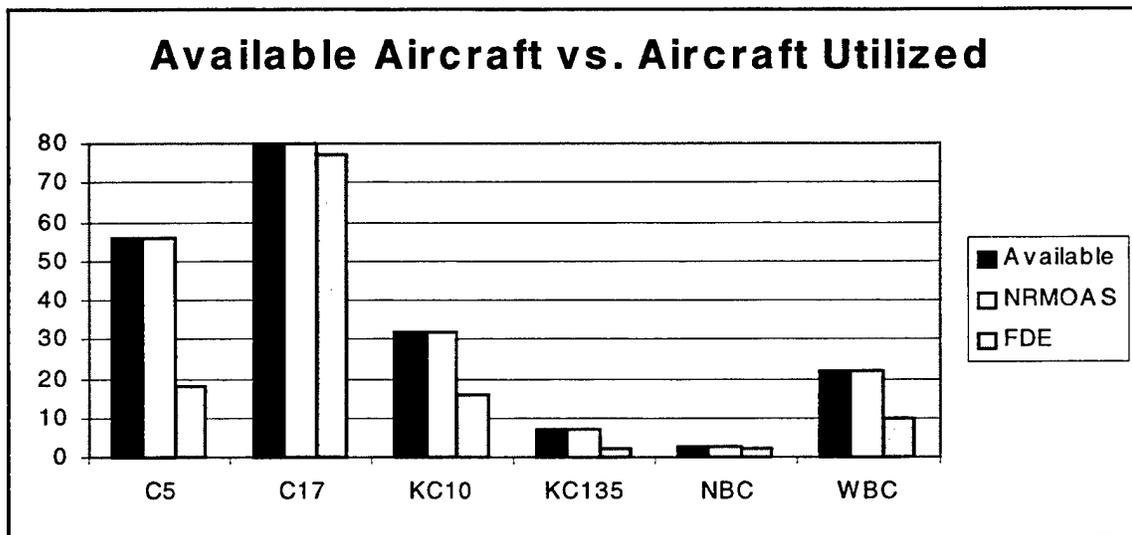

Figure 26. Due to the way that FDE uses the utilization rate, it effectively starts each deployment with one half of the number of aircraft available to NRMOAS. This allows NRMOAS to move more cargo faster, making it easier to meet its RDD requirements. Note that in the case of the C17 aircraft, FDE did not follow its own algorithm. We could not find a reason for this.

Another contributing factor in FDE's difficulties meeting delivery window requirements is its allocation algorithm. FDE's allocation is done as a biased stochastic assignment of lift assets directly proportional to the tonnage requirements of the unit and inversely proportional to the square of the unit's priority and its required arrival time (see Chaper IV, Section B). Each new trial is a new random number sequence that generates a new allocation of lift assets. This heuristic is designed simply to give a feasible starting point. (FDE URM, 1998, p. 3-16) A close examination of one unit which arrived on time with NRMOAS and 15 days late with FDE shows the flaws in this algorithm. The unit is an Army armored division with a RDD of 45 days. Its FDE asset allocation is shown in Table 4:

Number Allocated	Asset	Day Asset Became Available
1	WBP	12
1	WBP	20
2	LASH	15
1	RORO	25
4	LMSR	45
1	LASH	45
2	BB	65

Table 4. This table shows the allocation of assets to an Army armored division that arrives 15 days past its RDD (Scenario 1). Because of the random nature of the initial allocation heuristic, the unit was not allocated sufficient assets to arrive in theater on time. NRMOAS 's solution moved the Army division on 7 LMSR's and 11 RORO's, with closure on day 43.

Based on lift capabilities and tonnage requirements, the unit did not receive enough assets to make its RDD. Because the allocation is based on a random number, this type of situation can repeat itself during any trial solution for any type of unit. This would make it extremely difficult to determine whether a certain type of unit consistently slows the entire deployment, or uses up all of one type of asset.

Like NRMO, NRMOAS allocates assests based on minimizing the weighted sum of late and undelivered cargo penalties, subject to restrictions such as asset balance, asset payload,

and port and airfield capacity. In essence, NRMOAS sends the assets to where they will have the most positive effect on the overall deployment schedule. In NRMOAS's case, the Army armored division was loaded on 7 LMSR's and 11 RORO's, in combination with three other units with a similar RDD and destination. It arrived on day 43. Because NRMOAS gives an optimal utilization of assets, any shortfalls or slowdowns can be traced to their true cause, rather than being due to a poor random draw.

3.   Speed of Computation

Run time comparisons for the different scenarios are shown in Table 5.

	NRMOAS		FDE	
Scenario	Platform Used	Run Time	Platform Used	Run Time
1	PC, 32 MB RAM	38.96 min	Sun SPAC	5.34 min
2	PC 32 MB RAM	33.11 min	Sun SPARC	71 sec
3	PC, 500 MB RAM	3 hr, 49 min	Sun SPARC	61 sec *
	IBM RS6000, 595H	1 hr, 12 min		
4	IBM RS6000, 595H	2 hr, 10 min	Not Compared	

* Only resulted in one feasible solution before FDE crashed.

Table 5. The table show the run times for each scenario and what type of platform it was run on. For NRMOAS, memory allocation was more of a limiting factor than processor speed. Run times for FDE are based on 26 trial solutions except where noted.

NRMOAS, in searching for an optimal answer, requires significantly greater computation time than FDE. The FDE URM states (without proof and without precedent in the operations research literature) that if FDE makes between 25 and 75 trial runs, the resulting solution will be very close to a global optimum (FDE URM, 1998, p. 3-9). That would increase the run times for FDE by approximately three times; however, whenever any number of trial runs over 26 was requested, FDE crashed after number 26, requiring us to limit the number of trial runs. In the case of Scenario 3 FDE found 1 feasible solution and then crashed during trial 2. To avoid crashing, we simply set the number of trial runs to 1.

4.   Ease of Analysis of Output

The NRMOAS output file can be formatted by the user to display whatever data is desired. The user can suppress information that is not wanted, as well as display any additional information required. The output file gives a detailed breakdown of cargo, carrier, base, route and unit information, throughout the course of the deployment. The output file is constructed as comma-delimited input to a spreadsheet. This makes the output easy to work with since most users should have access to and some knowledge of spreadsheet operations. For example, all graphs depicting NRMOAS delivery information were created from the output file using Excel© spreadsheet utilities. NRMOAS's output report also allows easy infrastructure analysis. For example, the user can determine, using the output report, which bases, routes and assets were the most heavily used.

FDE files contain a large amount of information in a series of pre-formatted files (see Appendix A for detailed file descriptions). As with NRMOAS, these files give a detailed breakdown of cargo movement, carrier assignment, and base and route utilization. They are printed as space-delimited text that can be used as standalone reports or imported into spreadsheets. FDE also contains files that allow the user to request and view multiple graphs, to include model goal satisfaction and percent of units delivered by day. If the user desires information in some other format than that which FDE is designed to display, it must be created by hand from the output files. As with NRMOAS, this can be done using a standard spreadsheet, although a significant amount of data manipulation is required. FDE's high level of aggregation and limited ability to represent actual deployment networks makes it impractical to use for detailed infrastructure analysis.

V. CONCLUSIONS AND RECOMMENDATIONS

A.   CONCLUSIONS

The Force Deployment Estimator is a low resolution model that can be used to give quick lower bound solutions to generic force mobility questions. FDE's usefulness as a tool for detailed real world analysis, however, is severely hampered by its inadequete network representation. The limitations of at most four links in a path and the high level of aggregation required for embarkation nodes, make detailed analysis of actual deployment routes impossible. Exceeding these limitations causes the model to crash. To use FDE, a deployment network must be tailored to FDE's capabilities. This limits FDE's use to certain "off-the-shelf" scenarios that are known to work. FDE's high level of aggregation also applies to airfield and port services. Fuel capacities are not accounted for and MOG is generally unconstrained, assumptions that decrease FDE's usefulness as a detailed analysis tool.

When comparing similar scenarios, NRMOAS consistently out-performed FDE, achieving superior on-time delivery rates both for cargo and personnel. NRMOAS allows the user to input any network or deployment situation and receive an optimal solution and allows a high degree of resolution both in network and infrastructure design. This detail makes NRMOAS well-suited to in-depth analysis of unit movement, route and base use, and asset utilization. NRMOAS's solution gives the user the most efficient mix of available assets and routing required to complete a deployment. This allows the user to focus on key areas of analysis, without the concern that the results are based on a random allocation. Because NRMOAS can be run on any GAMS capable computer, it has a degree of portability that is not found with FDE, which is designed to run on SUN SPARC systems. NRMOAS would benefit from the inclusion of a more user-friendly interface. Additionally, NRMOAS lack of ability to

75

represent stochastic events could limit its applications in some areas.

B.   RECOMENDATIONS

If FDE is to be retained as a tool for analysis in J8/WAD, it requires major improvements in its ability to accurately represent deployment networks. The current limitations of at most four links in a path and FDE's apparent inability to handle multiple source nodes with small amounts of cargo must be corrected for FDE to be at all useful for analyzing actual deployment networks. The extreme difficulty in building files from scratch must also be corrected. Additionally, the initial allocation alogorithm should be looked at in an effort to improve its ability to assign assets. Furthermore, minor improvements to the GUI would make it much more tolerable. Finally, unsubstantiated claims of global optimality must be retracted.

NRMOAS's superior performance in on-time deliveries and higher level of resolution for networks and infrastructure make it a better tool for detailed analysis than FDE. J8/WAD should utilize NRMOAS for use in answering detailed mobility questions concerning actual deployment networks and infrastructure questions. While on-site testing by J8/WAD is recommended, we believe that NRMOAS will give J8/WAD an added dimension in mobility analysis that it currently does not possess with FDE.

APPENDIX A – ADDITIONAL FDE DETAILS

A. OUTPUT FILES

1. "fort.2", Solution File. This contains a rehash of all input data, a listing of how well FDE met its user assigned goals and all of the initial carrier allocation data. It is written in a format to allow it to be printed and read as is. (FDE URM, 1998, p.3-25)

2. "fort.3", History File. This contains details on all the events that occurred during the deployment simulation. It is divided into five sections:

    a. Section 1 contains the date and time the solution was found.

    b. Section 2 contains the path and unit data for link in the route network.

    c. Section 3 lists carrier data and assigns each carrier an index number. It is designed for use as a reference.

    d. Section 4 is a state definition table that is also designed for use as a reference.

    e. Section 5 shows the timing for each event that occurs during the simulation.

(FDE URM, 1998, p. 3-25)

3. "fort.10", Bar Chart Data File. This file holds the data to produce bar charts which can be used to display the following information:

    a. A lift objectives chart which shows how close the program came to meeting its required goals.

    b. A closure histogram which displays the closure for priority one units

    c. A dispersion histogram which displays the closure of priority one units.

    d. A cost histogram which displays the frequency of costs associated with unit movements.

e. A re-allocation histogram which shows the re-allocation of units. This chart is only

available when minimization of re-allocation is selected as a program goal.

(FDE URM, 1998, p. 3-28)

4. "fort.11", Line Graph Data File. This file contains the data needed to draw line charts.

These line charts can be used to display the arrival profile of each unit's cargo and personnel

over time. (FDE URM, 1998, p. 3-28)

5. "fort.12", Missions on Ground file. The first portion of this file lists the index values of each

carrier and each node. The rest of the file gives the numbers of each carrier type at each node,

per unit time. (FDE URM, 1998, p. 3-29)

6. "fort.13", Equipment on Ground File. The first part of the file lists the index values for load

types, node names and unit names. The rest of the file gives the tons of cargo moved through

each node, per unit, per unit time. (FDE URM, 1998, p. 3-30)

7. "fort.14", Fraction of Craft Utilized File. This file first lists index values for the carriers.

The rest of the file gives the number of carriers used by each unit per unit time. (FDE URM,

1998, p. 3-31)

8. "fort.15", Unit Craft Utilized File. The gives the number of carriers used by each unit per

unit time. (FDE URM, 1998, p. 3-31)

9. "fort.16", Unit Fraction of Actual Craft Utilized File. The first part of this file lists index

values for the carriers and units. The rest of the file gives the percentage of each type of carrier

used per unit per unit time. (FDE URM, 1998, p. 3-32)

10. "fort.75", Consolidated Graphics File. This is simply a consolidation of files "fort.12"

through "fort.16". This file is no longer needed as a separate file, but is still included in Version

3.1. (FDE URM, 1998, 3-33)

B. AIRCRAFT LOADING ALGORITHMS

The following rules and definitions apply to all algorithms:

1.   Class 1 carriers carry personnel only – no cargo.

2.   All carriers wait at a node for a full load if the current partial load contains personnel only and there are more passengers arriving. The carrier will wait only if waiting will improve the closure time of the unit. If waiting will extend the arrival time of the unit, the carrier will not wait for the arriving passengers.

3.   All cargo aircraft (Class 2 carriers) can carry bulk cargo.

4.   % Oversized – The proportion of the total cargo weight in short tons which is oversized cargo, when the load includes outsized cargo. The percentage is unit specific.

5.   % Outsized – The proportion of the total cargo weight in short tons which is outsized cargo, when the load also includes oversized cargo. This percentage is unit specific.

(FDE URM, 1998, p. 3-16)

FDE considers five separate loading cases.

Case 1: Load consists of bulk, over and out-sized cargo.

```
Total Load = carr_over * carr_%over + carr_out * carr_%out
                            100                      100

Max Outsized Load = carr_out * carr_%out
      100

Max Oversized Load = carr_over * carr_%over
                                    100

Max Bulk Load = Total Load - carr_over - carr_out

Max Passengers = carr_pax
```

Case 2: Load consists of bulk and out-sized cargo.

```
Total Load = carr_out

Max Outsized Load = carr_out

Max Bulk Load = Total Load - carr_out already loaded

Max Passengers = carr_pax
```

Case 3: Load consists of bulk and over-sized cargo.

```
Total Load = carr_over

Max Outsized Load = carr_over

Max Bulk Load = Total Load - carr_over already loaded

Max Passengers = carr_pax
```

Case 4: Load consists of bulk cargo.

```
Total Load = carr_bulk

Max Bulk Load = Total Load

Max Passengers = carr_pax
```

Case 5: Load consists only of passengers. The equations used are shown below:

```
Max Passengers = carr_pax0
```

(FDE URM, 1998, p. D-1)

The following logic loops are used to determine specific amounts of cargo moved:

Amount of Outsized Cargo Moved:

```
if (min (unit_over, carr_over) = 0), then
      out_moved = min(unit_out,carr_out)
else
      over_moved = min (unit_out, carr_%out / 100)
end if
```

Amount of Oversized Cargo Moved:

```
if (min (unit_out, carr_out) = 0), then
      over_moved = min(unit_over,carr_over)
else
      over_moved = min (unit_over, carr_%over / 100)
end if
```

Amount of Bulk Cargo Moved:

```
if (min (unit_out, carr_out) = 0), then
      if (min (unit_out, carr_out) = 0), then
            bulk_moved = min(unit_bulk, carr_bulk)
      else
            bulk_moved = min(unit_bulk, (carr_over-carr_bulk)
      endif
else
      if (min (unit_out, carr_out) = 0), then
            bulk_moved = min(unit_bulk, (unit_out, carr_out))
      else
            bulk_moved =

            min (unit_bulk, ((carr-out*carr_%out +
                  carr_over*carr_%over) / 100) -
                  unit_out - unit_over)
      endif
.endif
```

Number of Passegers Moved:

```
if (over-moved and out_moved =0 and bulk_moved =0), then
      pax = moved = min(unit_pax, carr_pax0)
else
      pax = moved = min(unit_pax, carr_pax)
endif
```

(FDE URM, 1998, p. D-3)

C. MODELING ASSUMPTIONS

1. All arcs are bi-directional. Delivery arcs may be used for re-assignment, but re-assignment

arcs may not be used for delivery.

2. Carriers are assigned to unit source nodes. Each carrier will move all of an assigned unit's

cargo and personnel before it is re-assigned.

3. Carriers that do not allow units to meet their required delivery dates will not be assigned to that unit.

4. Since there are a limited number of carriers that can carry out-sized cargo, they will not be assigned to carry sustainment (normally bulk) cargo until all out-sized cargo has been moved.

5. Carrier re-assignment is based on minimizing the following:

Q = Active Carriers * Re-allocation Days * (Goal Time – Current Time) *

Unit Priority / Total Tonnage Left

6. Personnel only carriers wait at nodes until they are full or no more personnel are enroute to that node.

7. Unit cargo that arrives from different sources can be aggregated upon arrival to a common node.

8. Unit arrival is defined as delivery of 100% of personnel and cargo.

9. Nodes and links may be degraded by enemy action.

10. Mine fields do not affect air links.

11. Carriers cannot anticipate when a full node will have space to service them. Therefore, loaded carriers at a full node will simply wait until they can be unloaded and empty carriers will not go to full a node until it has room.

12. If the variable input mode is used, all variables are statistically independent.

(FDE URM , 1998, p. A-1)

APPENDIX B – ADDITIONAL NRMO DETAILS

A. INPUT FILES

1. <u>Gamsagg.set</u>. Gamsagg.set is designed to work with a pre-processor program, but is also fully functional as a stand alone file. The pre-processor takes line information from the TPFDD and aircraft capacity data from files contained in the Airlift Flow Model (AFM), the main simulation used by the Airlift Mobility Command and combines them into a format usable by NRMO. For users with a non-Air Force TPFDD, or users without AFM, the required information can be hard wired into gamsagg.set with no degradation of capabilities. For this analysis, NRMO was used with hardwired information. Gamsagg.set first lists all aircraft and all bases which make up the model. Bases are broken down into embarkation bases, forward operating bases, points of departure, enroute bases, aerial refueling points, recovery bases and supernodes (aggregate bases). Base locations are input using longitude and latitude. Airfield capacity, in terms of Maximum on Ground (MOG) and fuel available are also included. Additionally, this file contains all the unit data that would be taken from a TPFDD, to include unit identification, point of origin, point of departure, cargo demand available to load date, and required delivery date.

2. <u>Routes.inc</u>. Routes.inc sets up the network over which the deployment is carried out. It identifies deployment routes, backchannel (re-deployment) routes and adjacent nodes and arcs. In addition, it defines which aircraft can travel over which arcs. This file also is used to designate arcs as Category 1, an AMC categorization that is given to flights over water. An aircraft flying a Category 1 arc must carry an extra 10% fuel.

3. <u>Scenario.inc</u>. Scenario.inc contains items specific to a given scenario. This includes the breakdown of aerial refueling points, tanker bed down sites, and crew staging bases. It

delineates between military and Civil Reserve Air Fleet (CRAF) aircraft. It identifies those aircraft that can be refueled by tankers, as well as what aerial refueling points, bed down bases, and forward operating bases can be used by which aircraft and which routes. Scenario also sets the theater recovery policy; "allrec", meaning always use recovery routes, "somerec" meaning sometimes use recovery routes or "norec" meaning never use recovery routes. Recocery routes refer to those routes which contain bases where an aircraft can be serviced after executing a quick-turn mission. Recovery policy is set separately for each supor node. Any super node containing a port should have a "norec" policy since ships would not be required to execute quick turn missions.Scenario.inc contains the data for on load time, off load time and enroute recovery and maintenance time. Penalties for late and non-delivered cargo, as well as rewards for crew rest are calculated here. In addition, shuttle and aerial refueling parameters are contained in this file.

4. Acdat.inc. Acdat.inc is called by scenario.inc. It contains aircraft specific data, to include; relative size (to apply to MOG considerations), speed, allowable utilization rate and the rate at which aircraft will be allocated to the deployment. In addition, this file scales the weights of the cargo and passengers in order to calculate the aircraft's "critical" payload at each range. The file also includes a fuel consumption table, which contains data for each type of aircraft used.

5. Calc.inc. Calc.inc is also called by scenario.inc. This file contains many of the calculations that are needed elsewhere in NRMO. These calculations include; utilization hours, distances and flight times (including ground time), fuel consumption rates and MOG calculations. Calc.inc contains an abort function that will abort a mission that cannot be completed within the allotted time of the deployment .

B. OUTPUT FILE

The output file is divided into several sections. The first section shows the value of the objective function. The next section lists the number of missions flown, by aircraft. The third section displays cargo related information. This includes cargo delivered over time by category of aircraft (military or CRAF), undelivered cargo and undelivered PAX. The fourth section concentrates on information needed for base analysis. It breaks down the number of aircraft per day that flow through a base, the fuel and MOG that they use and the cargo that they carry. The final section summarizes the total time, flying time and ground time spent on each route. In all sections, minimum, maximum and mean values are shown. The report can be tailored to display any information desired.

APPENDIX C – GLOSSARY OF ACRONYMS / DEFINITIONS

AFM	Airlift Flow Model
AFSAA	Air Force Studies and Analysis Agency
AF/XOM	Air Force Chief of Staff for Mobility
AMC	Air Mobility Command
Bulk	Cargo with a high weight to volume ratio. Ex: ammunition, palletized cargo, batteries, etc.
carrier	generic name for any vehicle that conveys cargo or pax
carr_item	Indicates carrier capacity of an item. Ex: carr_bulk is how much bulk cargo a carrier can move.
FDE	Force Deployment Estimator
GUI	Graphic User Interface
item_moved	Indicates the amount of an item that has been moved. Ex. bulk_moved is how much bulk cargo has been moved.
JCS	Joint Chiefs of Staff
MOG	Maximum on Ground
MOM	Mobility Optimization Model
MRS BURU	Mobility Requirements Study Bottoms Up Review
MSC	Military Sealift Command
MTW	Major Theater War
NPS	Naval Postgraduate School
NRMO	Naval Postgraduate School / RAND Mobility Optimizer
Over	Cargo with a low weight to volume ratio. Ex: Trucks, trailers, etc.
%Over	Percent of cargo that is oversized.

Out	Cargo that will only fit on ships or wide bodied aircraft. Ex: tank, infantry fighting vehicle.
%Out	Percent of cargo that is outsized.
Pax	Personnel. In FDE, it is the number of personnel that a plane can carry while carrying cargo.
Pax0	In FDE, the number of personnel a plane can carry if carrying no cargo.
quick turn	Unloading an aircraft in theater without servicing. Ships will not execute quick turn missions.
recovery base	A base where an aircraft can receive services after a quick turn mission
WAD	Warfighting Analysis Division

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